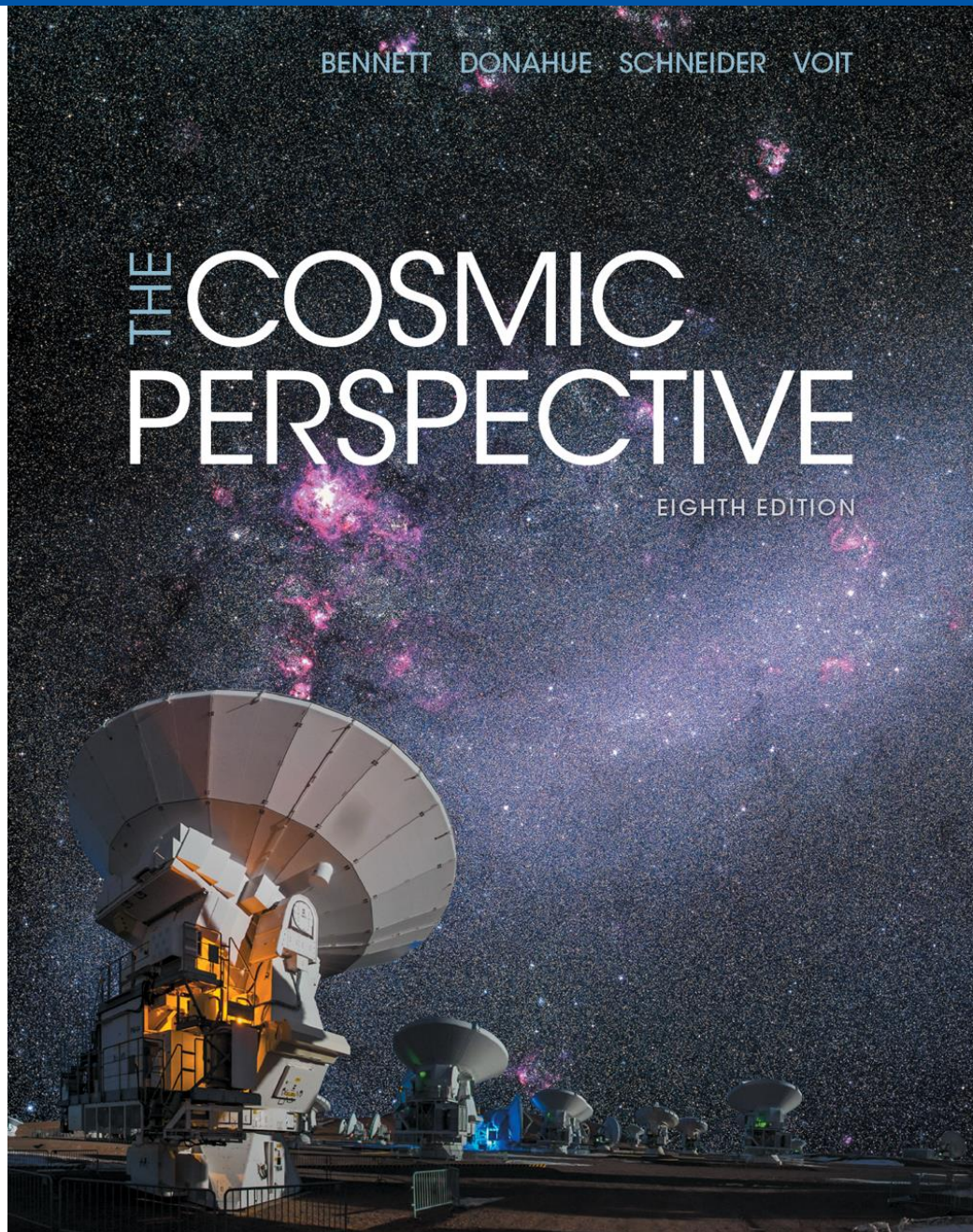
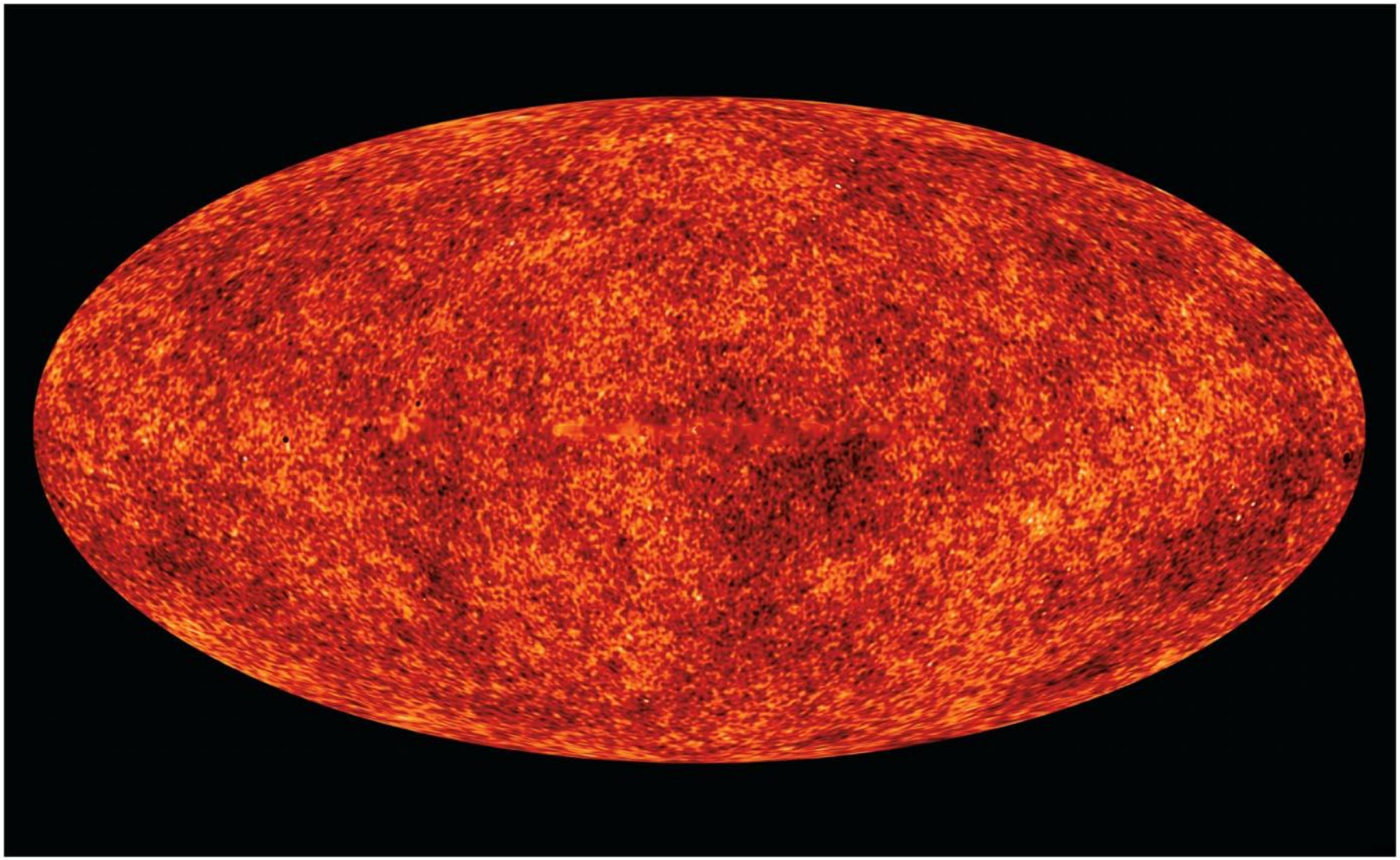
Chapter 22: The Birth of the Universe



© 2017 Pearson Education, Inc.

The Birth of the Universe



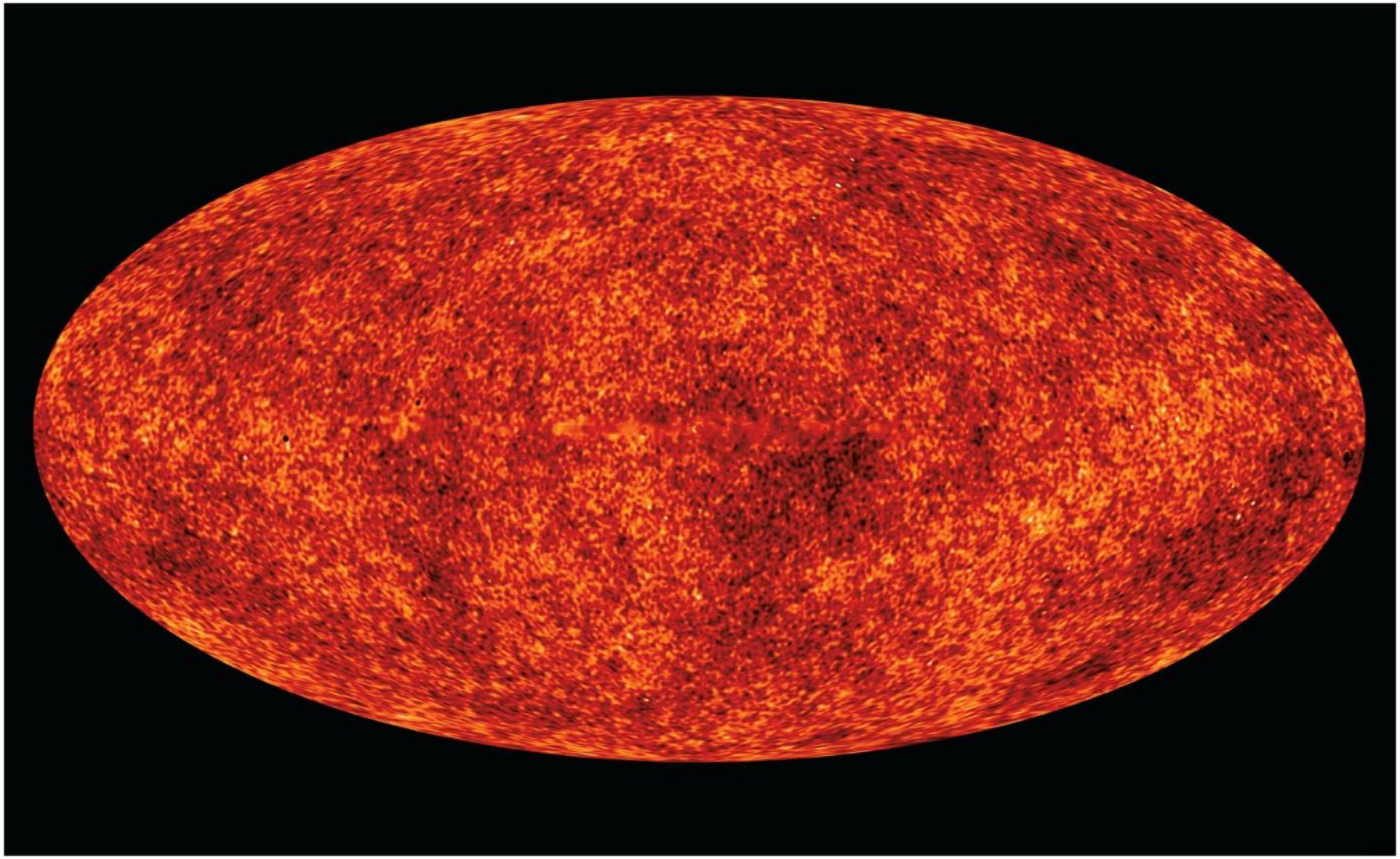
© 2017 Pearson Education, Inc.

22.1 The Big Bang Theory

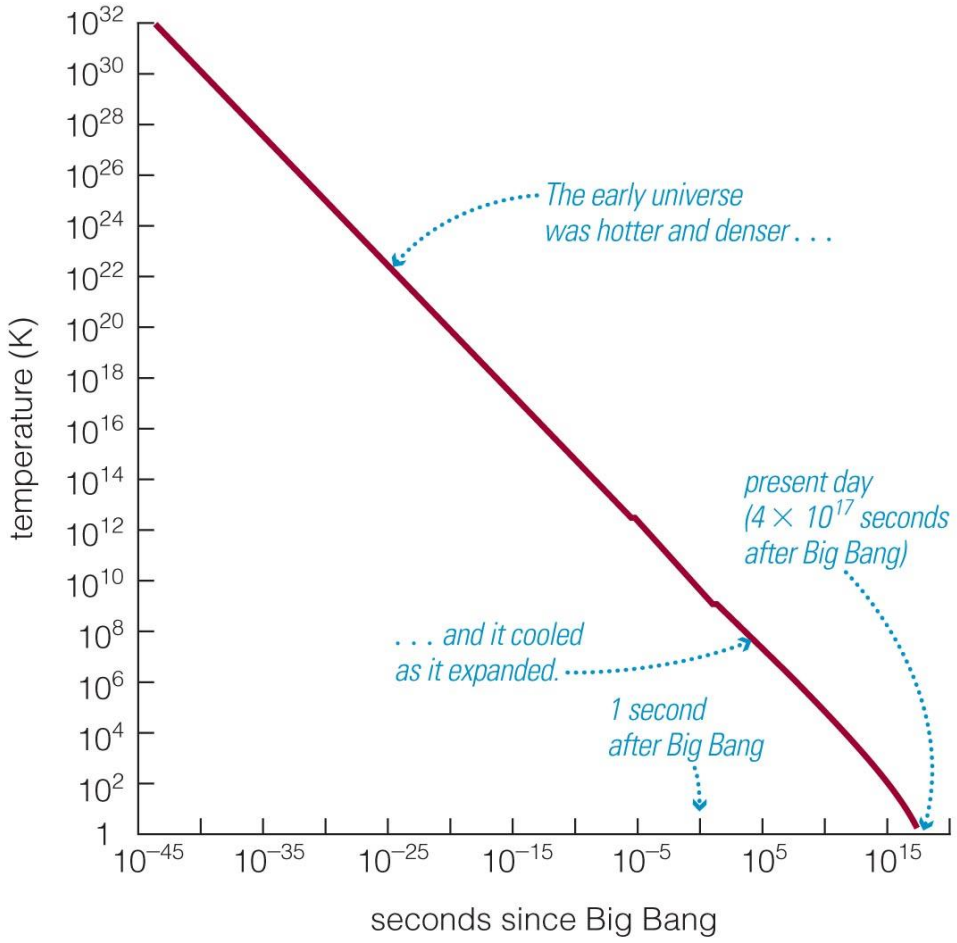
- Our goals for learning:
  - **What were conditions like in the early universe?**
  - **How did the early universe change with time?**

© 2017 Pearson Education, Inc.

What were conditions like in the early universe?

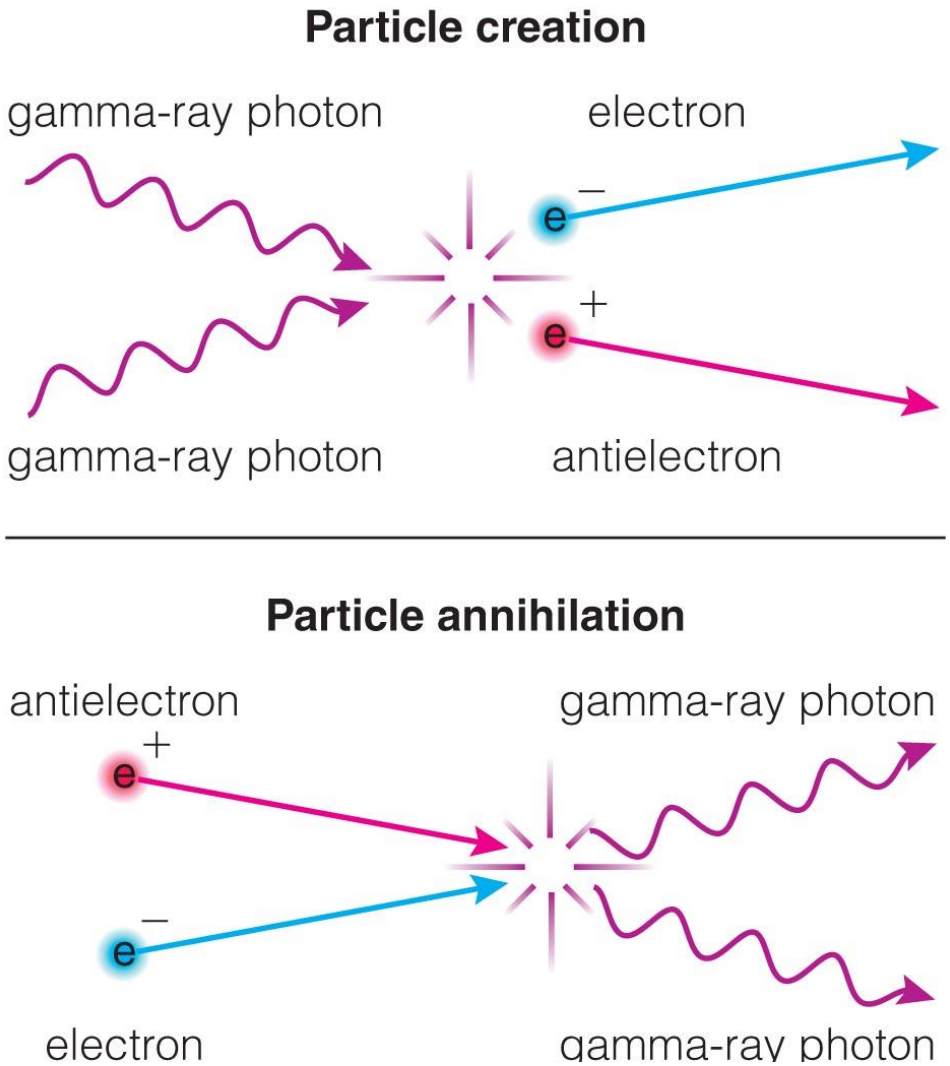


© 2017 Pearson Education, Inc.



- The early universe must have been extremely hot and dense.

© 2017 Pearson Education, Inc.

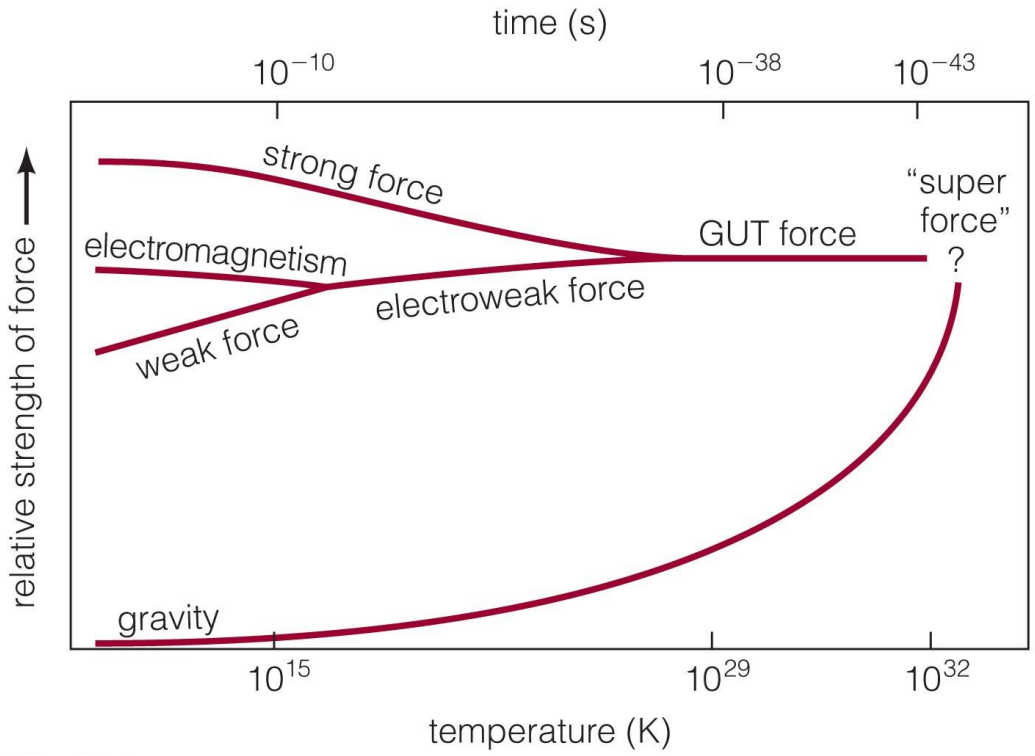


- Photons converted into particle–antiparticle pairs and vice versa.

$$E = mc^2$$

- The early universe was full of particles and radiation because of its high temperature.

© 2017 Pearson Education, Inc.



- Four known forces in universe:
  - ***Strong force***
  - ***Electromagnetism***
  - ***Weak force***
  - ***Gravity***

© 2017 Pearson Education, Inc.

Thought Question

Which of the four forces keeps you from sinking to the center of Earth?

A. gravity
B. electromagnetism
C. strong force
D. weak force

© 2017 Pearson Education, Inc.

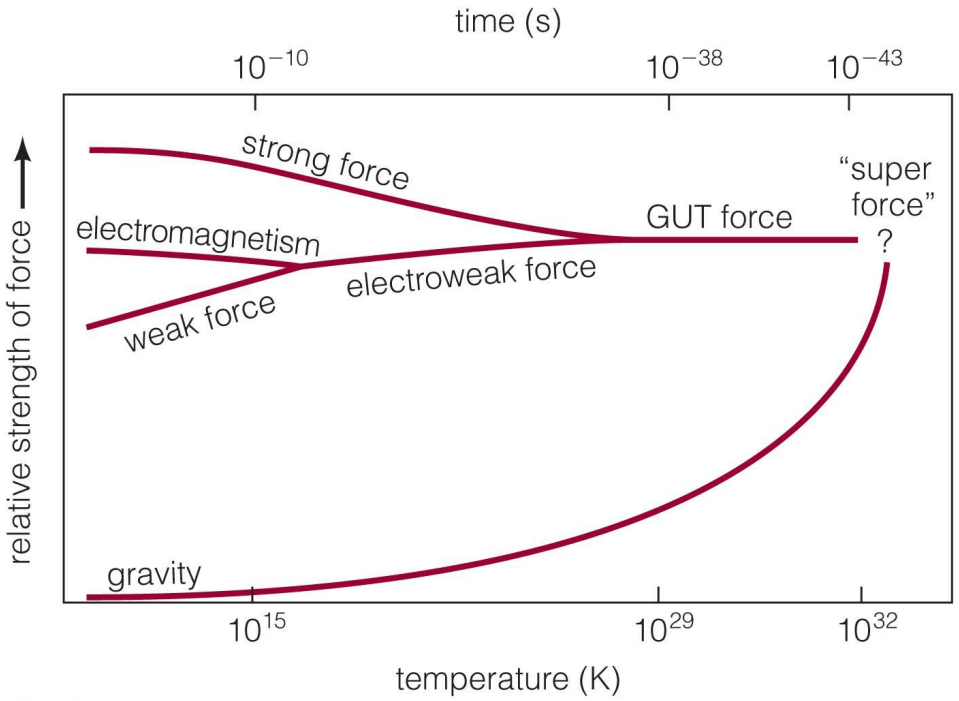
Thought Question

Which of the four forces keeps you from sinking to the center of Earth?

A. gravity
B. electromagnetism
C. strong force
D. weak force

© 2017 Pearson Education, Inc.

- Do forces unify at high temperatures?



- Four known forces in universe:

Strong force

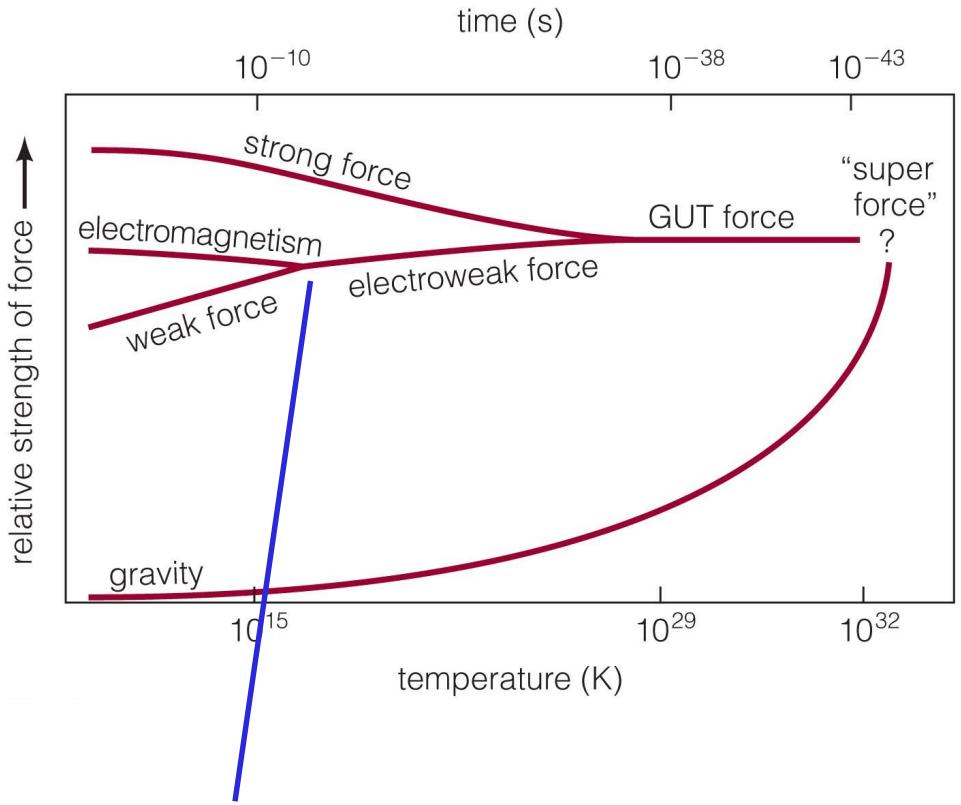
Electromagnetism

Weak force

Gravity

© 2017 Pearson Education, Inc.

- Do forces unify at high temperatures?



Yes!
(Electroweak)

- Four known forces in universe:

Strong force

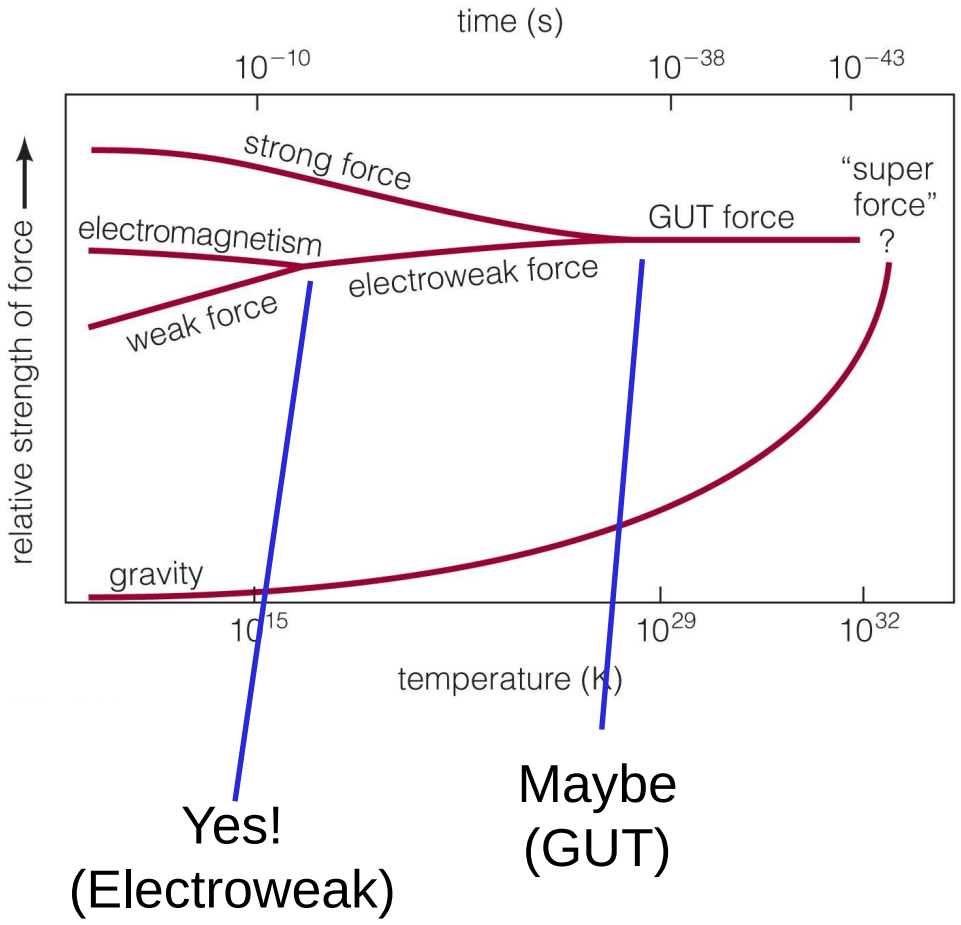
Electromagnetism

Weak force

Gravity

© 2017 Pearson Education, Inc.

- Do forces unify at high temperatures?



- Four known forces in universe:

Strong force

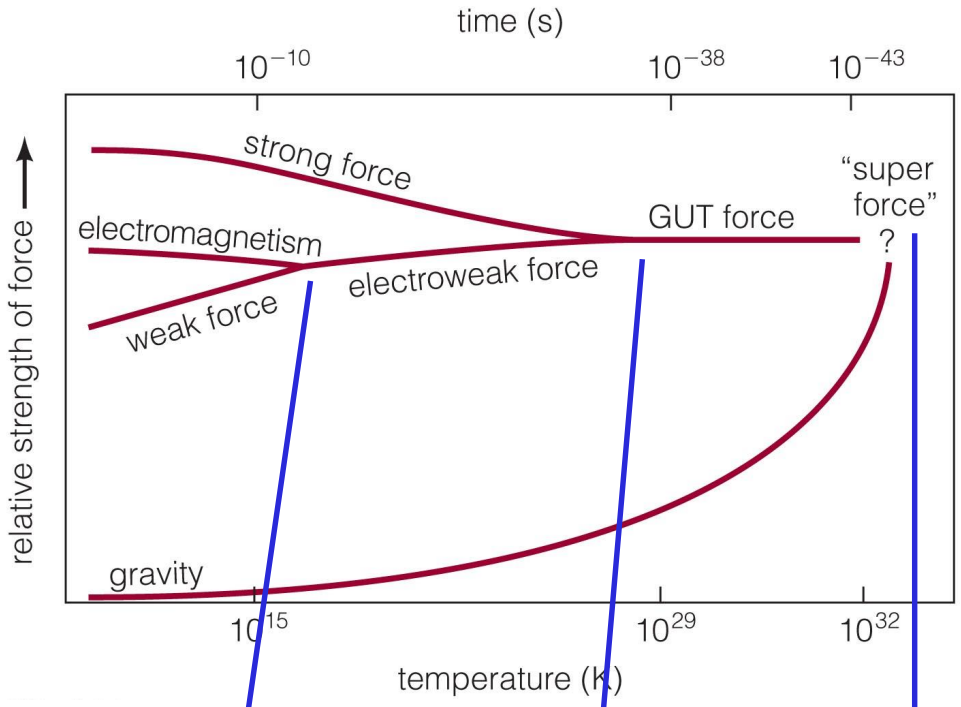
Electromagnetism

Weak force

Gravity

© 2017 Pearson Education, Inc.

- Do forces unify at high temperatures?



Yes!
(Electroweak)

Maybe
(GUT)

Who knows?
(Theory of Everything)

- Four known forces in universe:

Strong force

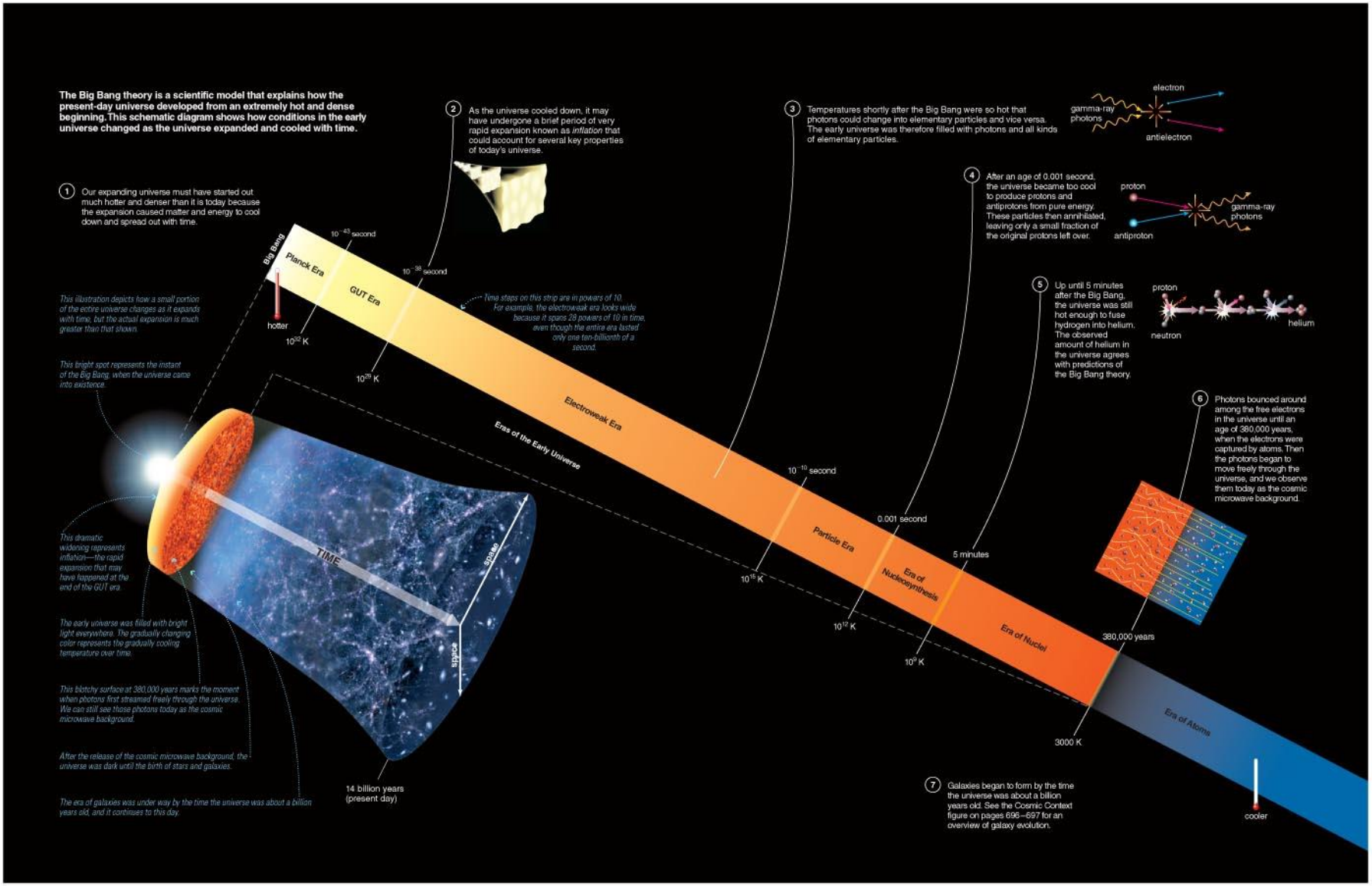
Electromagnetism

Weak force

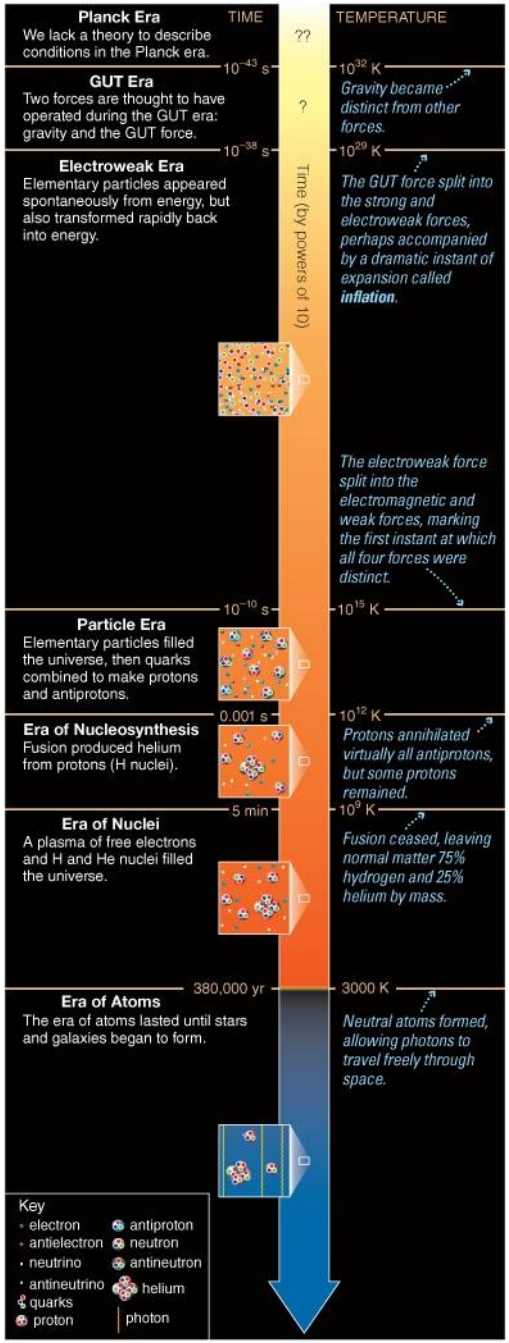
Gravity

© 2017 Pearson Education, Inc.

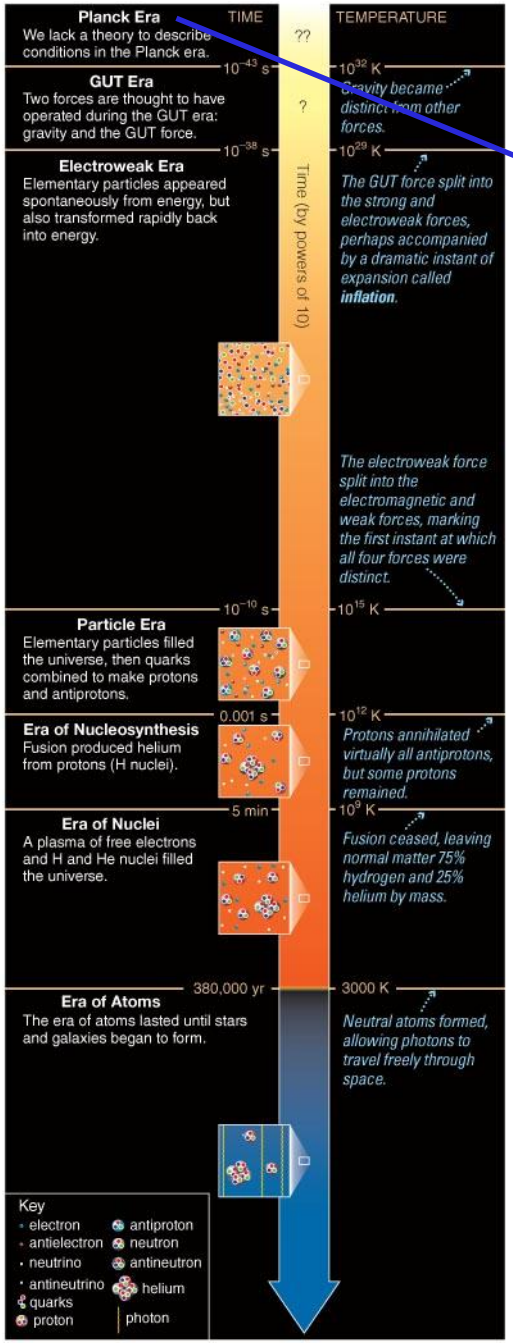
How did the early universe change with time?


The Big Bang theory is a scientific model that explains how the present-day universe developed from an extremely hot and dense beginning. This schematic diagram shows how conditions in the early universe changed as the universe expanded and cooled with time.
1 Our expanding universe must have started out much hotter and denser than it is today because the expansion caused matter and energy to cool down and spread out with time.
2 As the universe cooled down, it may have undergone a brief period of very rapid expansion known as inflation that could account for several key properties of today's universe.
3 Temperatures shortly after the Big Bang were so hot that photons could change into elementary particles and vice versa. The early universe was therefore filled with photons and all kinds of elementary particles.
electron
gamma-ray photons
antielectron
4 After an age of 0.001 second, the universe became too cool to produce protons and antiprotons from pure energy. These particles then annihilated, leaving only a small fraction of the original protons left over.
proton
gamma-ray photons
antiproton
5 Up until 5 minutes after the Big Bang, the universe was still hot enough to fuse hydrogen into helium. The observed amount of helium in the universe agrees with predictions of the Big Bang theory.
proton
neutron
helium
6 Photons bounced around among the free electrons in the universe until an age of 380,000 years, when the electrons were captured by atoms. Then the photons began to move freely through the universe, and we observe them today as the cosmic microwave background.
7 Galaxies began to form by the time the universe was about a billion years old. See the Cosmic Context figure on pages 696–697 for an overview of galaxy evolution.
This illustration depicts how a small portion of the entire universe changes as it expands with time, but the actual expansion is much greater than that shown.
This bright spot represents the instant of the Big Bang, when the universe came into existence.
This dramatic widening represents inflation—the rapid expansion that may have happened at the end of the GUT era.
The early universe was filled with bright light everywhere. The gradually changing color represents the gradually cooling temperature over time.
This blotchy surface at 380,000 years marks the moment when photons first streamed freely through the universe. We can still see those photons today as the cosmic microwave background.
After the release of the cosmic microwave background, the universe was dark until the birth of stars and galaxies.
The era of galaxies was under way by the time the universe was about a billion years old, and it continues to this day.
Time steps on this strip are in powers of 10. For example, the electroweak era looks wide because it spans 28 powers of 10 in time, even though the entire era lasted only one ten-billionth of a second.
Big Bang
Planck Era
GUT Era
Electroweak Era
Particle Era
Era of Nucleosynthesis
Era of Nuclei
Era of Atoms
Eras of the Early Universe
10^{-43} second
10^{-38} second
10^{-10} second
0.001 second
5 minutes
380,000 years
10^{32} K
10^{28} K
10^{15} K
10^{12} K
10^{9} K
3000 K
hotter
cooler
TIME
space
space
14 billion years (present day)

© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
?
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
Time (by powers of 10)
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

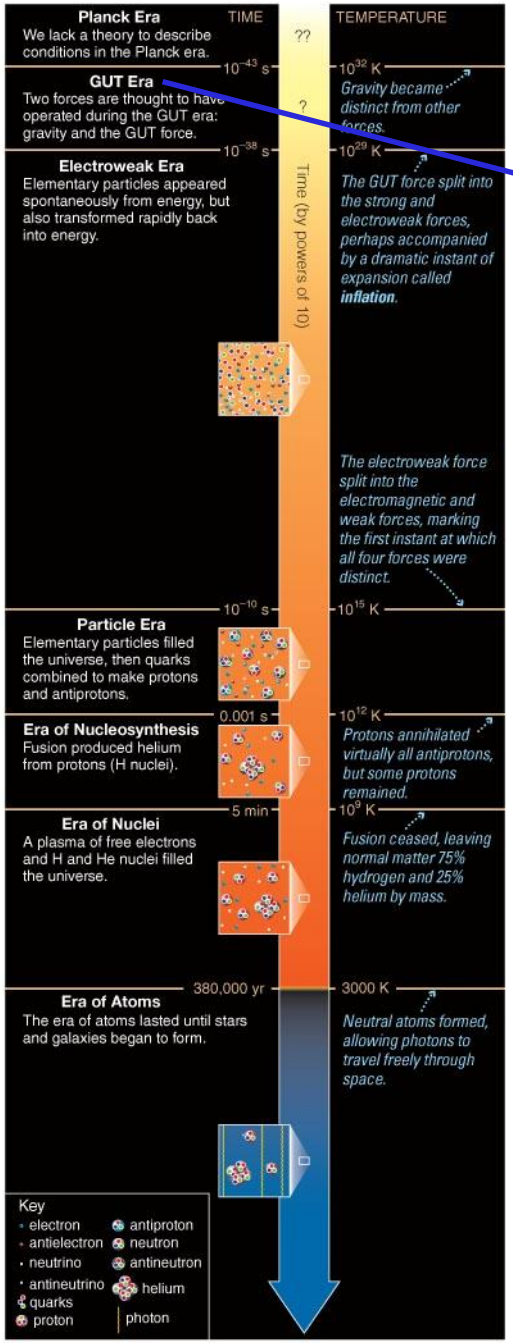
© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
?
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
Time (by powers of 10)
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

Planck era

- Before Planck time (~10^{-43} second)
- No theory of quantum gravity

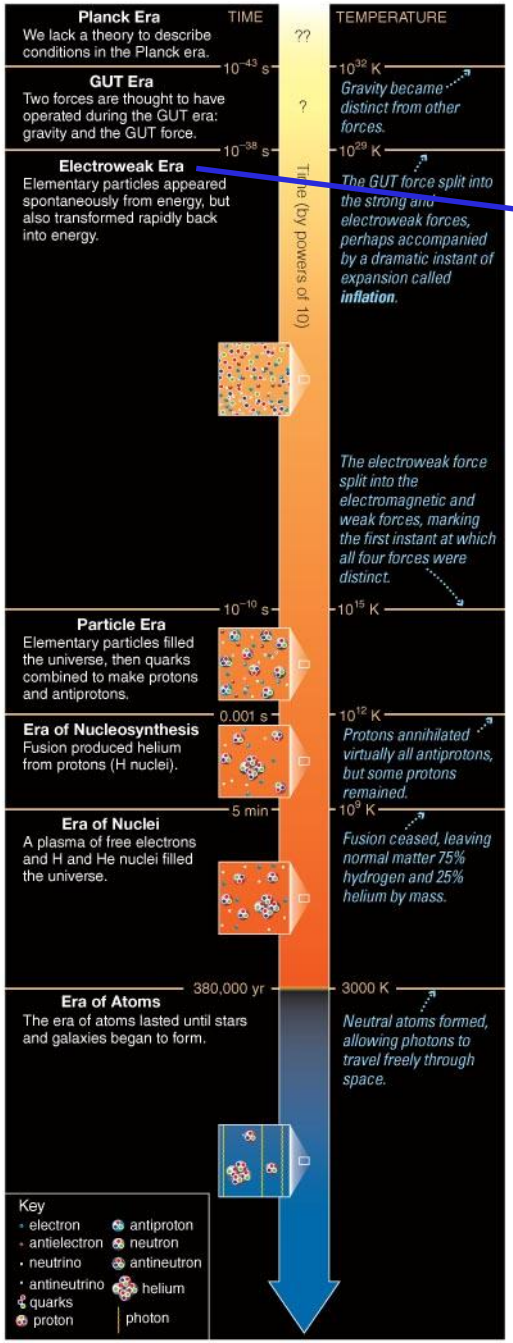
© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
?
10^{-38} s
10^{28} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
Time (by powers of 10)
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

GUT era

- Lasts from Planck time (~10^{-43} second) to end of GUT force (~10^{-38} second)

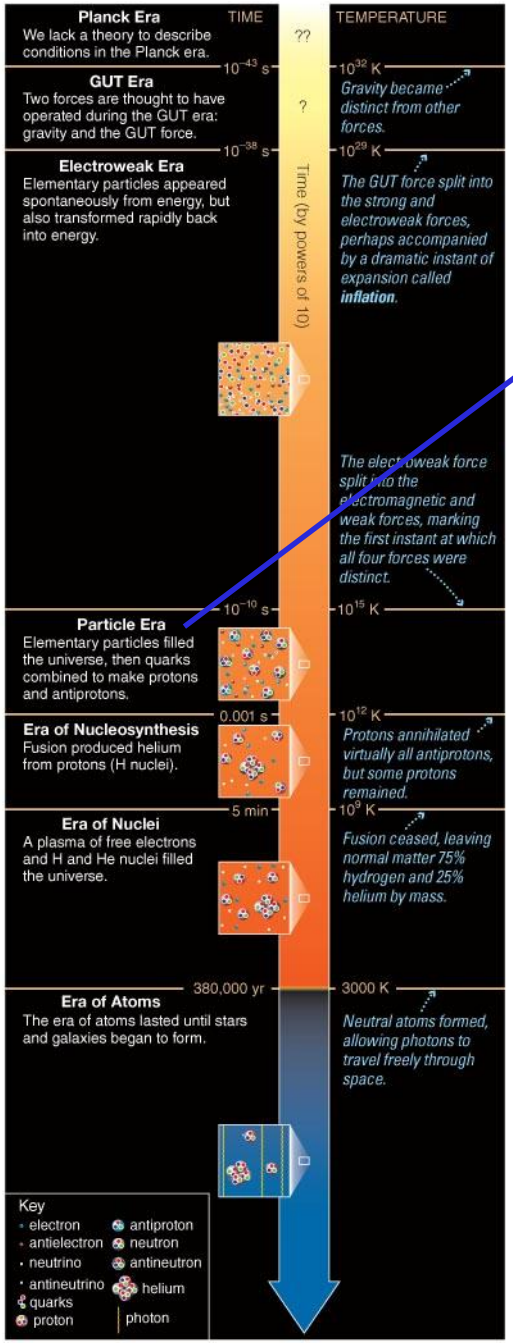
© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
?
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
Time (by powers of 10)
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

Electroweak era

- Lasts from end of GUT force (~10^{-38} second) to end of electroweak force (~10^{-10} second).

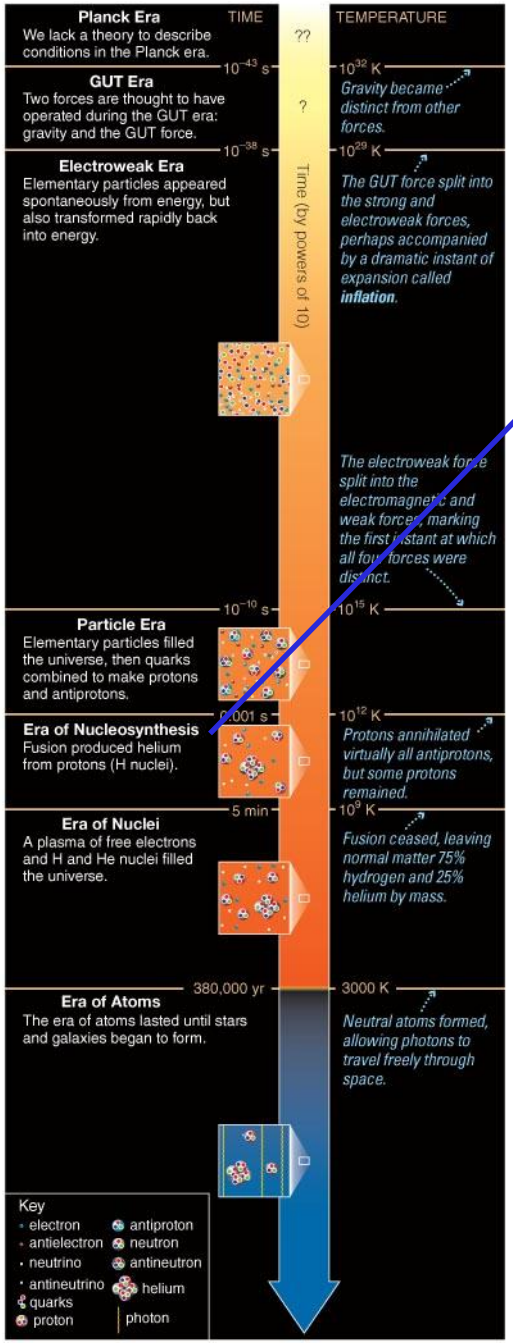
© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
?
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
Time (by powers of 10)
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

Particle era

- Amounts of matter and antimatter nearly equal (roughly 1 extra proton for every 10^9 proton–antiproton pairs!)

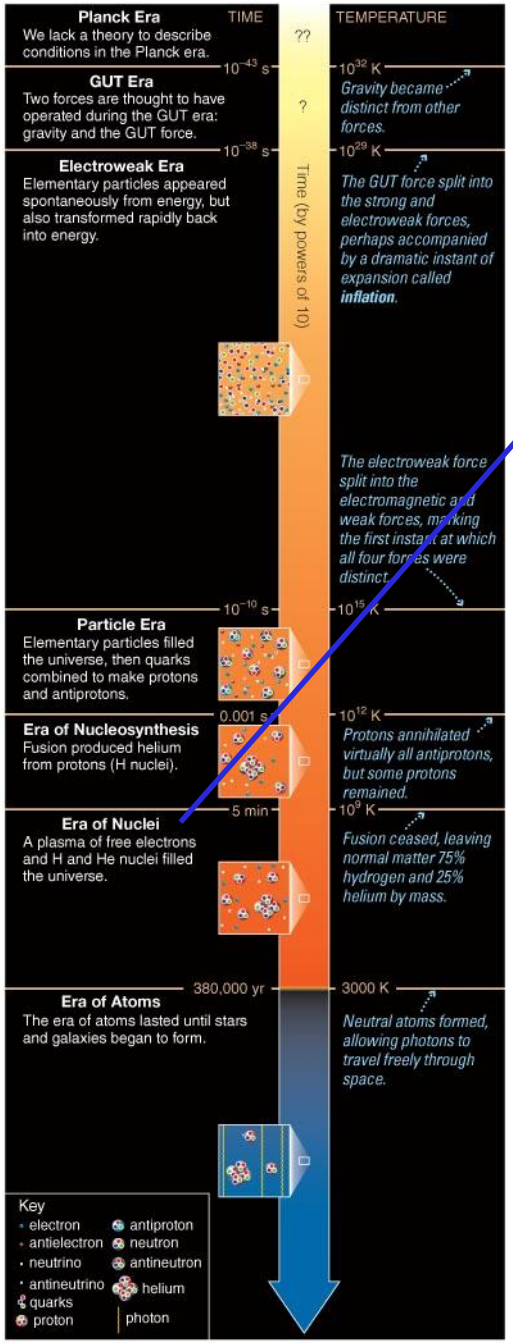
© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
?
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
Time (by powers of 10)
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

Era of nucleosynthesis

- Begins when matter annihilates remaining antimatter at ~ 0.001 second.
- Nuclei begin to fuse.

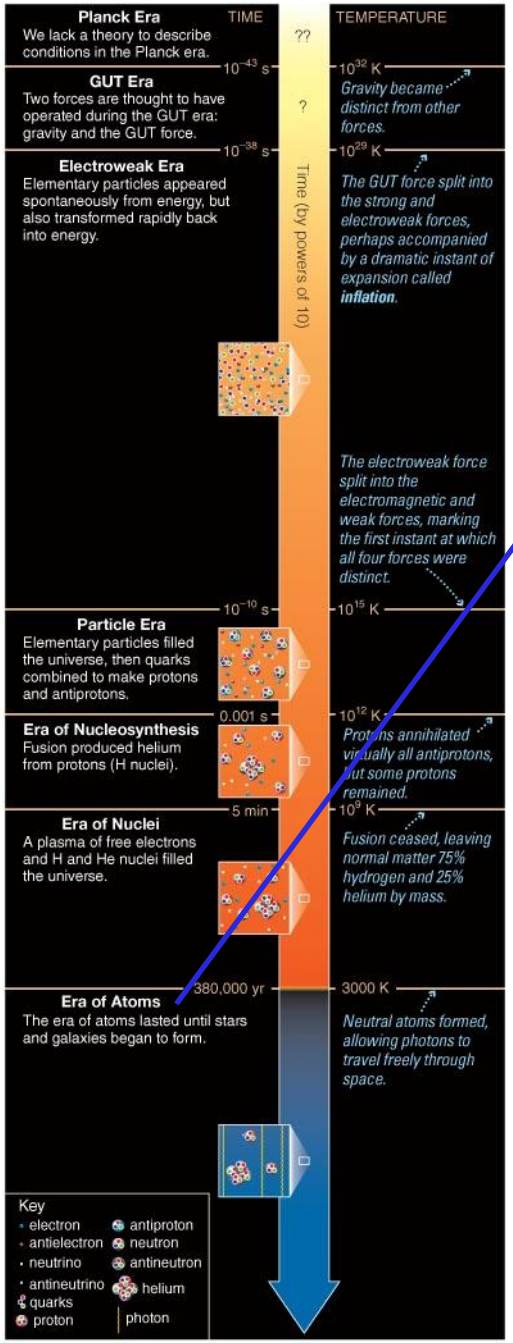
© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
?
Time (by powers of 10)
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

Era of nuclei

- Helium nuclei form at age ~ 3 minutes.
- Universe became too cool to blast helium apart.

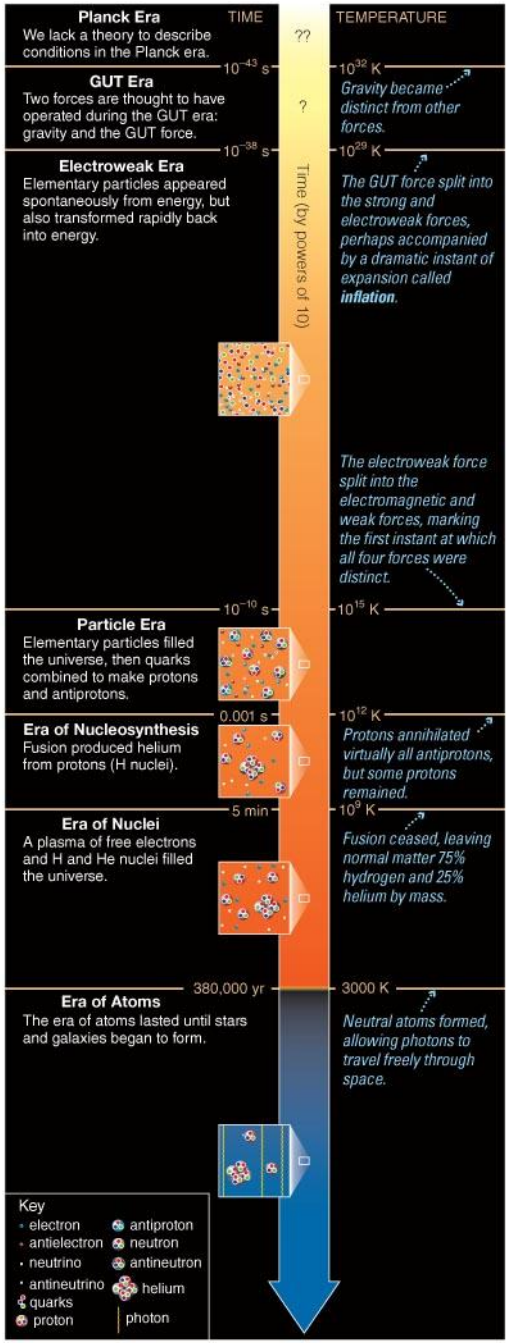
© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
?
Time (by powers of 10)
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

Era of atoms

- Atoms form at age ~ 380,000 years.
- Background radiation released.

© 2017 Pearson Education, Inc.


Planck Era
We lack a theory to describe conditions in the Planck era.
TIME
TEMPERATURE
??
10^{-43} s
10^{32} K
GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.
Gravity became distinct from other forces.
?
10^{-38} s
10^{29} K
Electroweak Era
Elementary particles appeared spontaneously from energy, but also transformed rapidly back into energy.
The GUT force split into the strong and electroweak forces, perhaps accompanied by a dramatic instant of expansion called inflation.
Time (by powers of 10)
The electroweak force split into the electromagnetic and weak forces, marking the first instant at which all four forces were distinct.
10^{-10} s
10^{15} K
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.
0.001 s
10^{12} K
Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).
Protons annihilated virtually all antiprotons, but some protons remained.
5 min
10^{9} K
Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.
Fusion ceased, leaving normal matter 75% hydrogen and 25% helium by mass.
380,000 yr
3000 K
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.
Neutral atoms formed, allowing photons to travel freely through space.
Key
electron
antielectron
neutrino
antineutrino
quarks
proton
antiproton
neutron
antineutron
helium
photon

Era of galaxies

- Galaxies form at age ~ 1 billion years.

© 2017 Pearson Education, Inc.

What have we learned?

- **What were conditions like in the early universe?**
  - The early universe was so hot and so dense that radiation was constantly producing particle–antiparticle pairs and vice versa.
- **How did the early universe change with time?**
  - As the universe cooled, particle production stopped, leaving matter instead of antimatter.
  - Fusion turned remaining neutrons into helium.
  - Radiation traveled freely after formation of atoms.

© 2017 Pearson Education, Inc.

22.2 Evidence for the Big Bang

- Our goals for learning:
  - **How do observations of the cosmic microwave background support the Big Bang theory?**
  - **How do the abundances of elements support the Big Bang theory?**

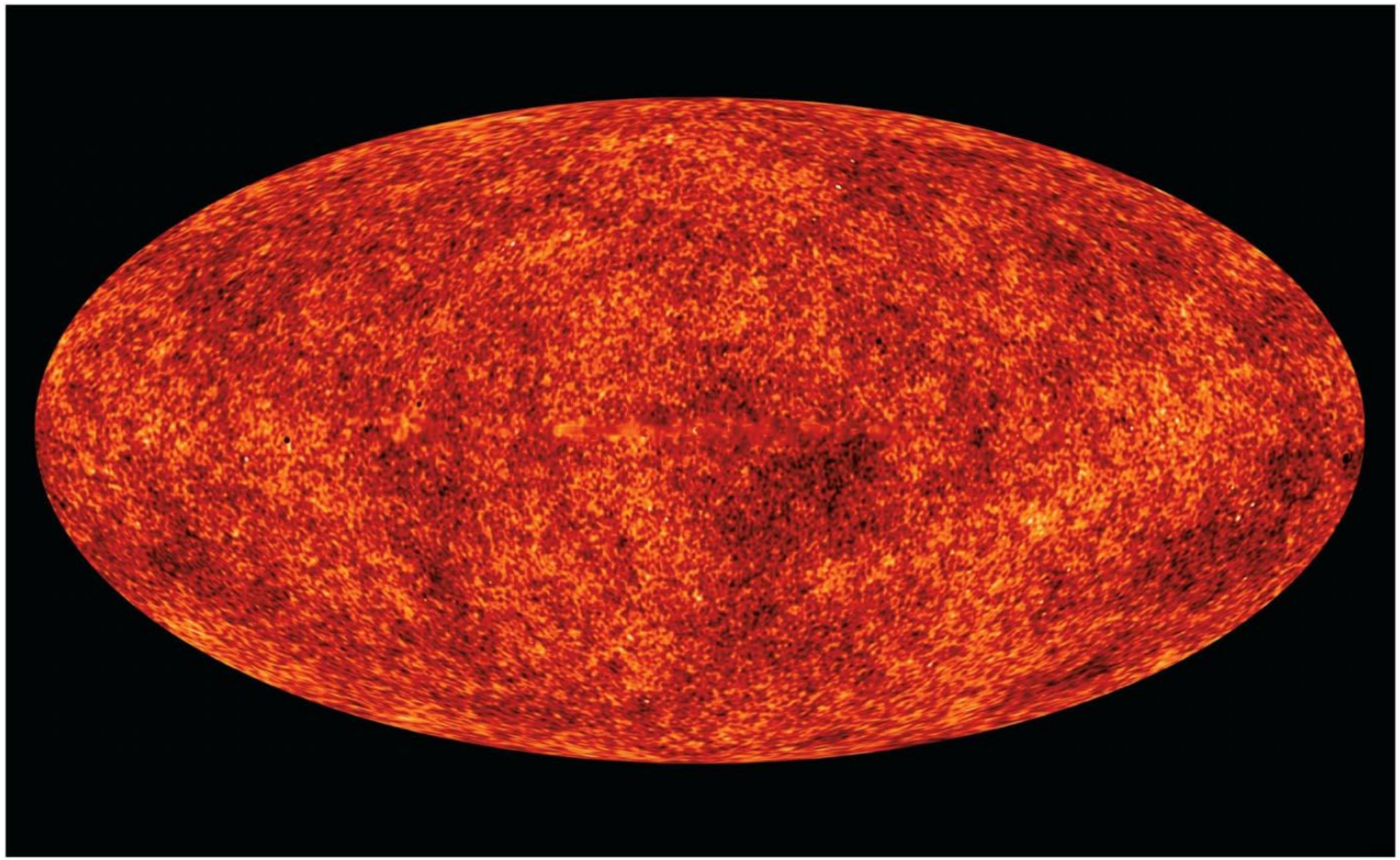
© 2017 Pearson Education, Inc.

Primary Evidence

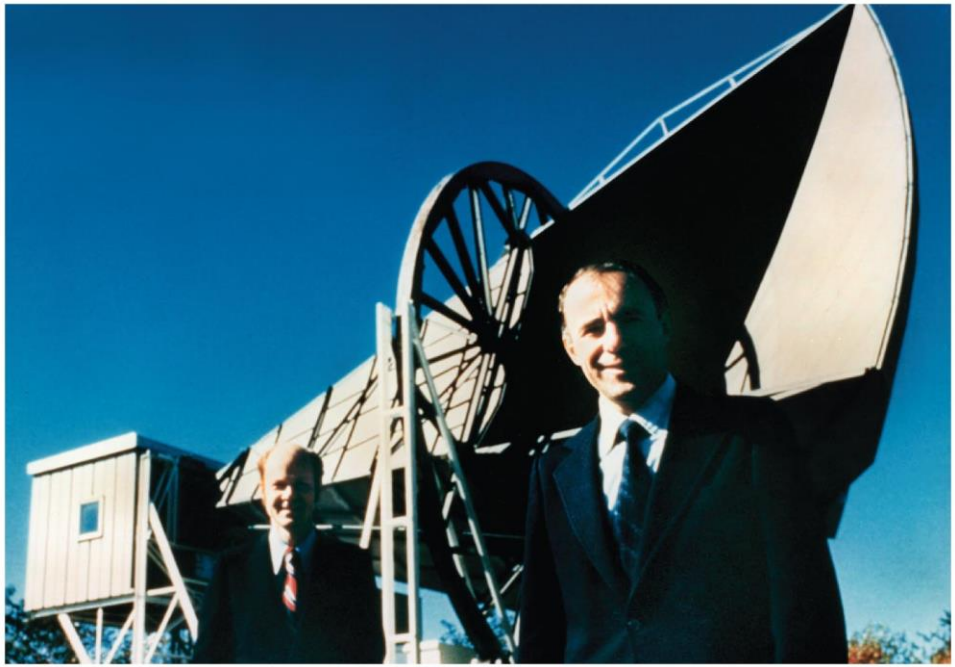
1. We have detected the leftover radiation from the Big Bang.
2. The Big Bang theory correctly predicts the abundance of helium and other light elements.

© 2017 Pearson Education, Inc.

How do observations of the cosmic microwave background support the Big Bang theory?

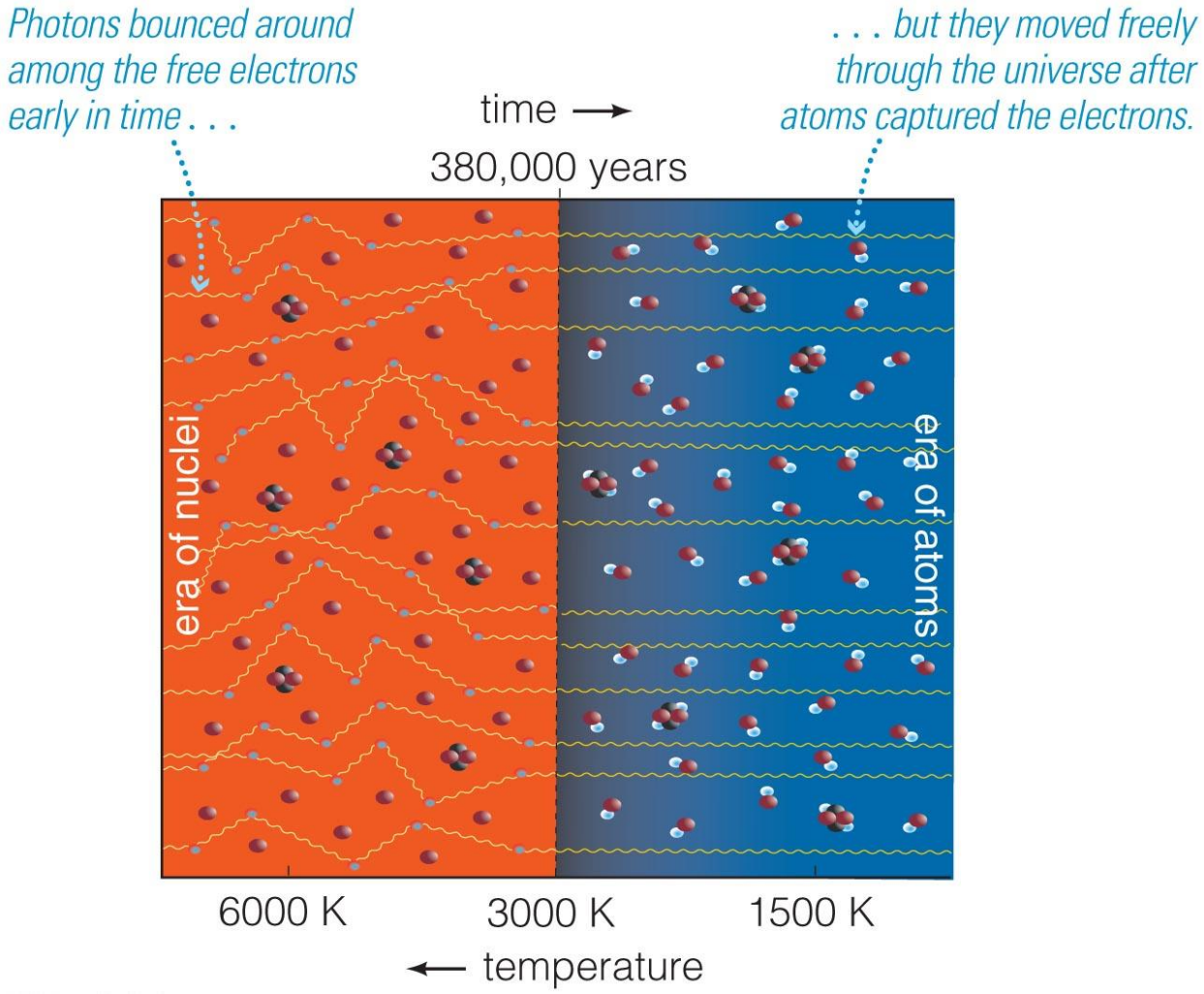


© 2017 Pearson Education, Inc.



- The ***cosmic microwave background***—the radiation left over from the Big Bang—was detected by Penzias and Wilson in 1965.

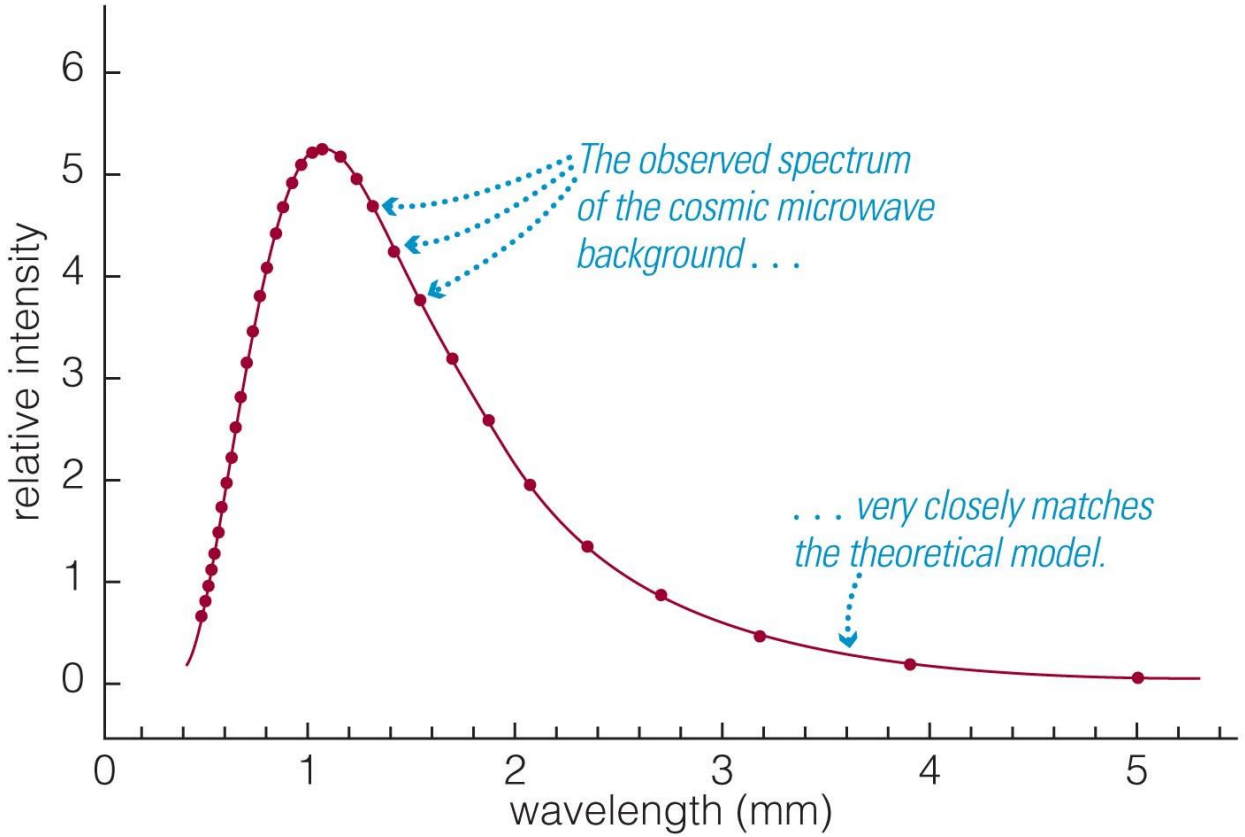
© 2017 Pearson Education, Inc.


Photons bounced around among the free electrons early in time . . .
. . . but they moved freely through the universe after atoms captured the electrons.
time →
380,000 years
era of nuclei
era of atoms
6000 K
3000 K
1500 K
← temperature

- Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3000 K: *visible/IR*.

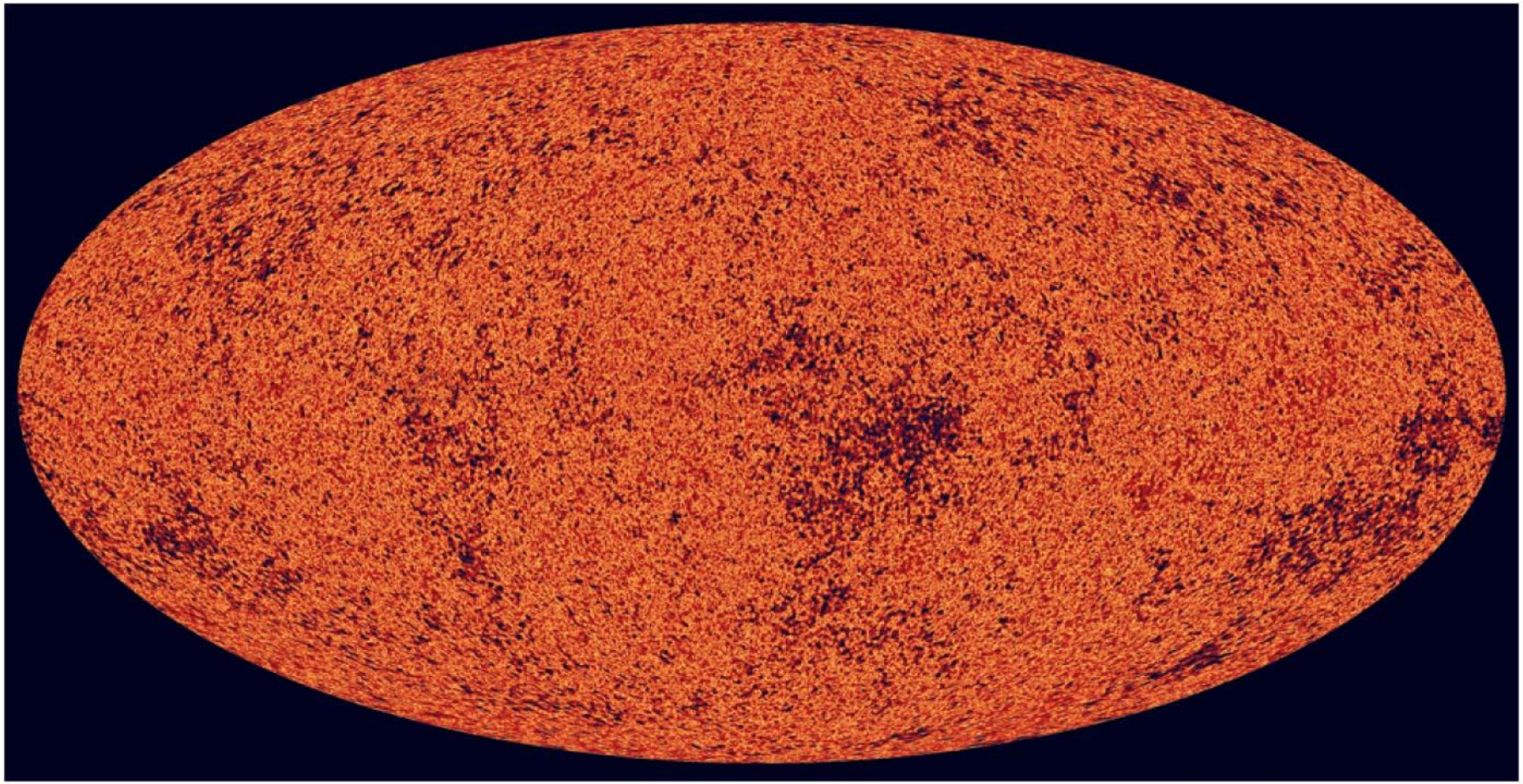
© 2017 Pearson Education, Inc.

- Background has perfect thermal radiation spectrum at temperature 2.73 K.



- Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*.

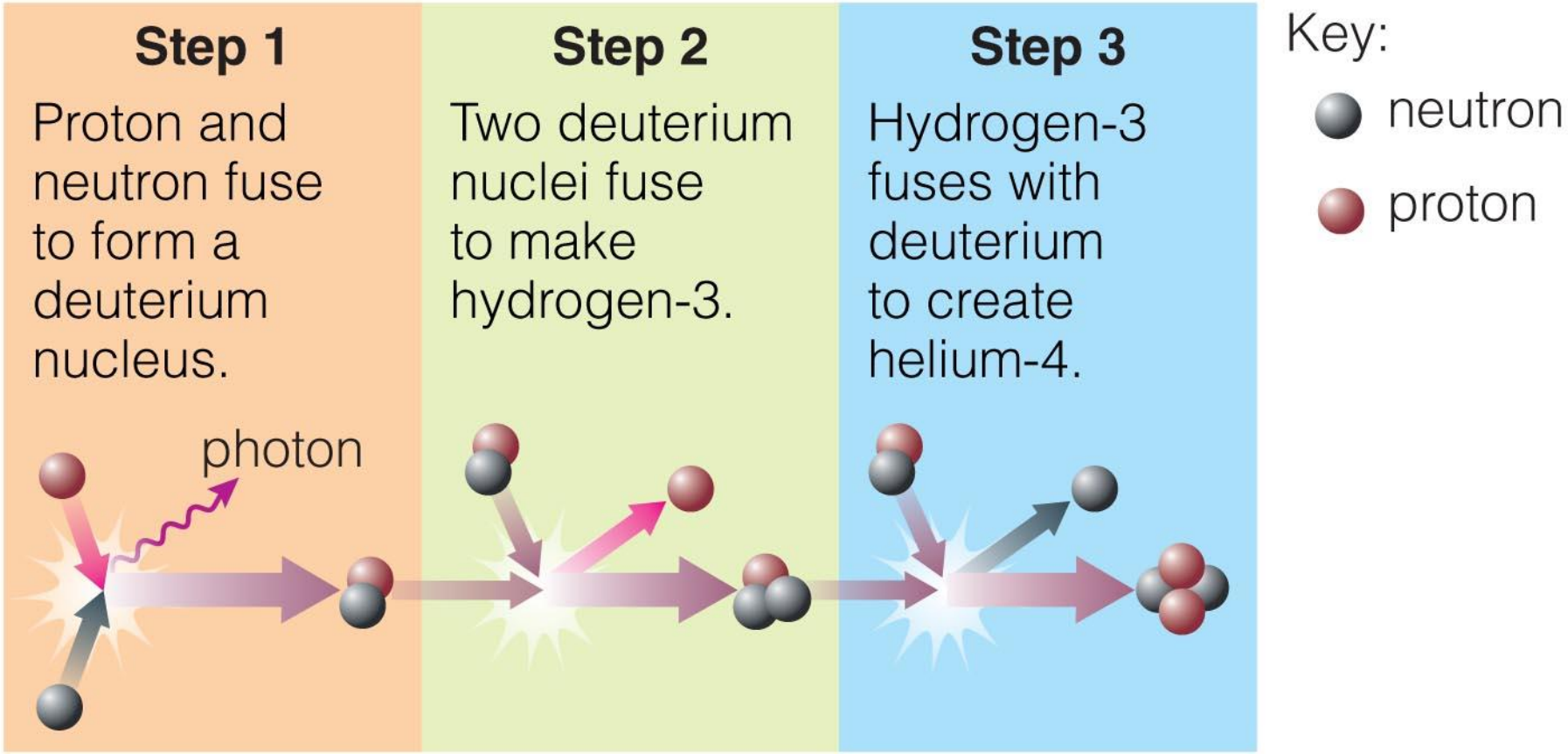
© 2017 Pearson Education, Inc.



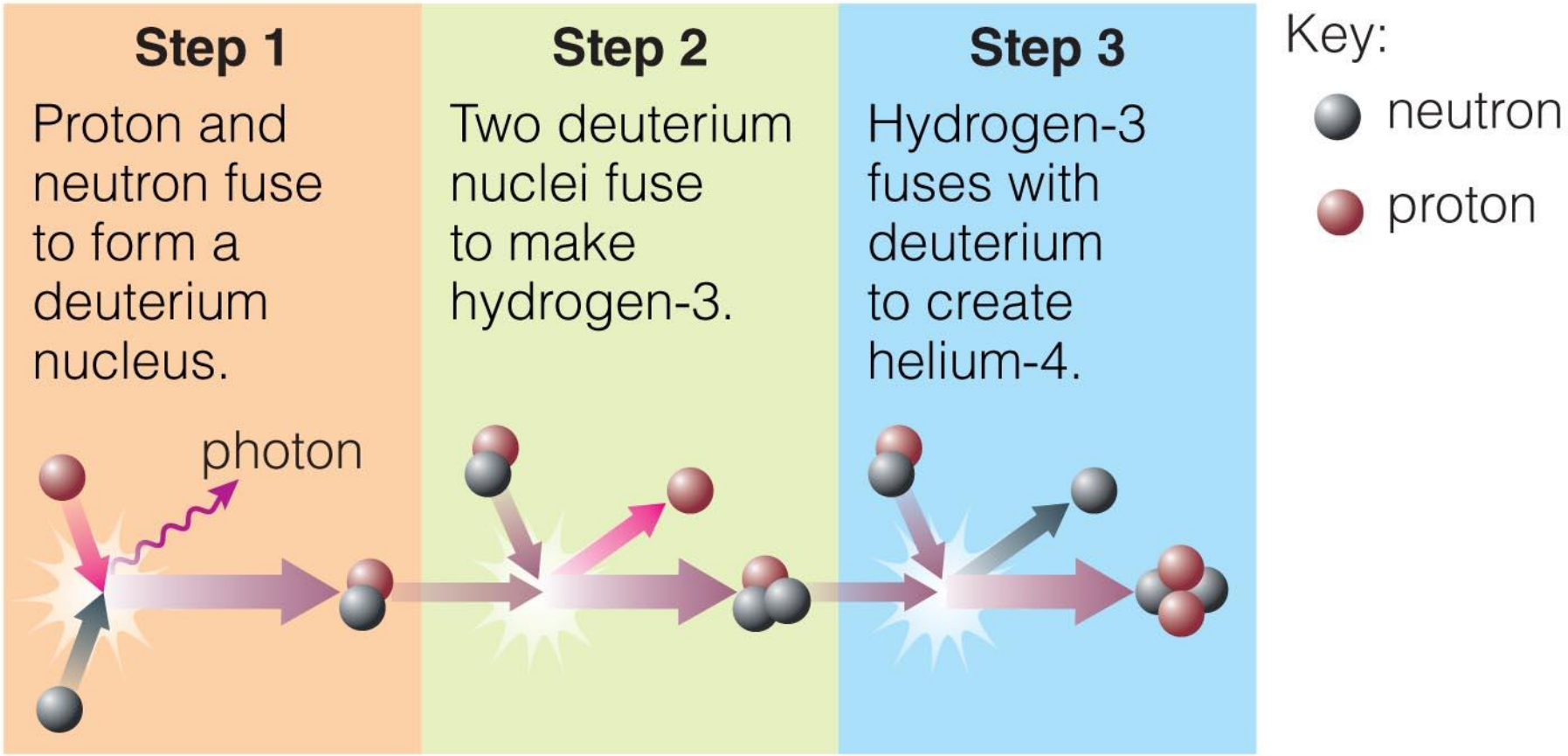
- *Planck* gives us detailed baby pictures of structure in the universe.

© 2017 Pearson Education, Inc.

How do the abundances of elements support the Big Bang theory?

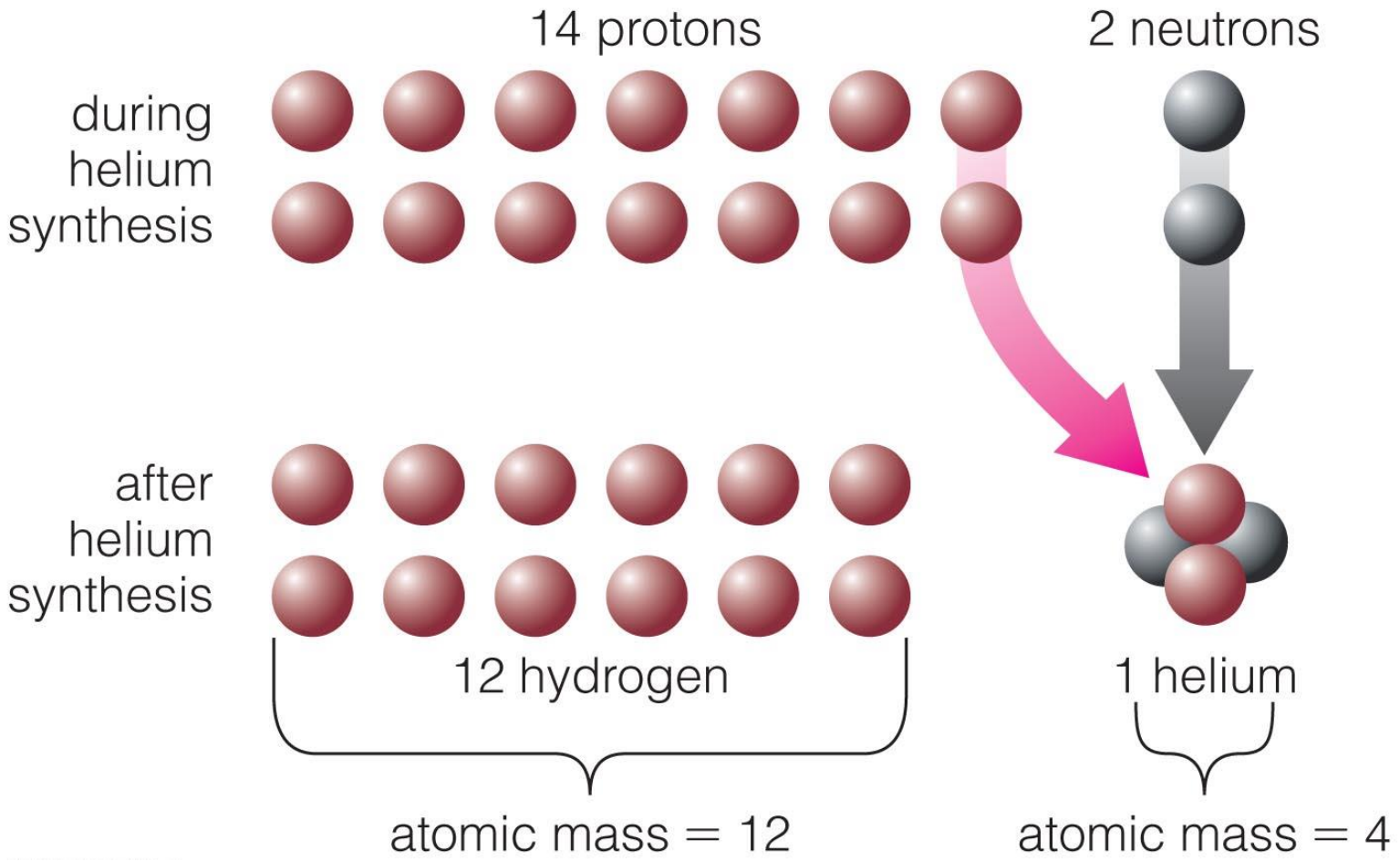


© 2017 Pearson Education, Inc.



- Protons and neutrons combined to make long-lasting helium nuclei when universe was ~ 3 minutes old.

© 2017 Pearson Education, Inc.



- Big Bang theory prediction: 75% H, 25% He (by mass). This prediction matches observations of primordial gases.

© 2017 Pearson Education, Inc.

Thought Question

Which of these abundance patterns is an unrealistic chemical composition for a star?

A. 70% H, 28% He, 2% other
B. 95% H, 5% He, less than 0.02% other
C. 75% H, 25% He, less than 0.02% other
D. 72% H, 27% He, 1% other

© 2017 Pearson Education, Inc.

Thought Question

Which of these abundance patterns is an unrealistic chemical composition for a star?

A. 70% H, 28% He, 2% other
B. 95% H, 5% He, less than 0.02% other
C. 75% H, 25% He, less than 0.02% other
D. 72% H, 27% He, 1% other

© 2017 Pearson Education, Inc.

What have we learned?

- **How do observations of the cosmic microwave background support the Big Bang theory?**
  - Radiation left over from the Big Bang is now in the form of microwaves—the cosmic microwave background—which we can observe with a radio telescope.
- **How do the abundances of elements support the Big Bang theory?**
  - Observations of helium and other light elements agree with the predictions for fusion in the Big Bang theory.

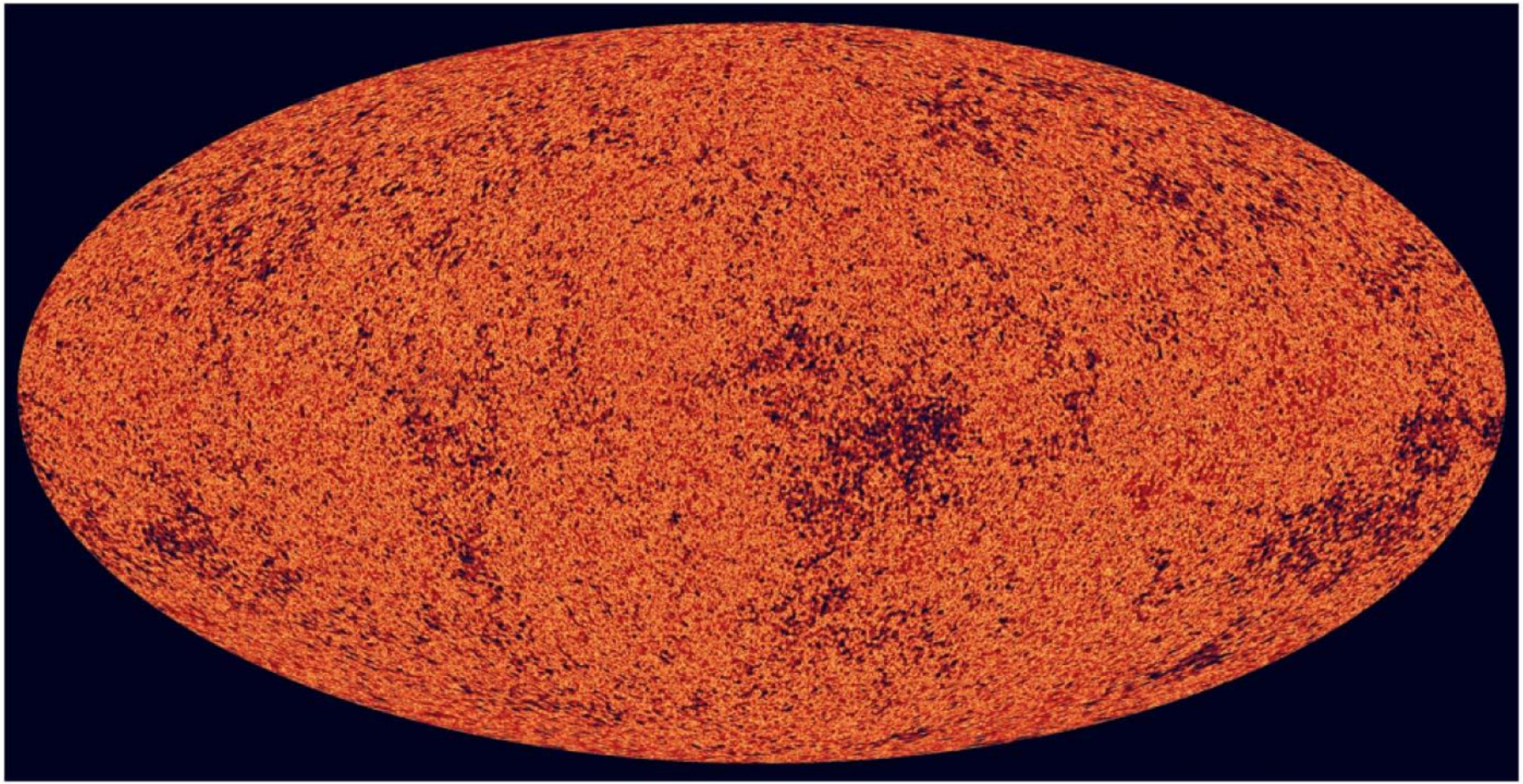
© 2017 Pearson Education, Inc.

22.3 The Big Bang and Inflation

- Our goals for learning:
  - **What key features of the universe are explained by inflation?**
  - **Did inflation really occur?**

© 2017 Pearson Education, Inc.

What key features of the universe are explained by inflation?



© 2017 Pearson Education, Inc.

Mysteries Needing Explanation

1. Where does structure come from?
2. Why is the overall distribution of matter so uniform?
3. Why is the density of the universe so close to the critical density?

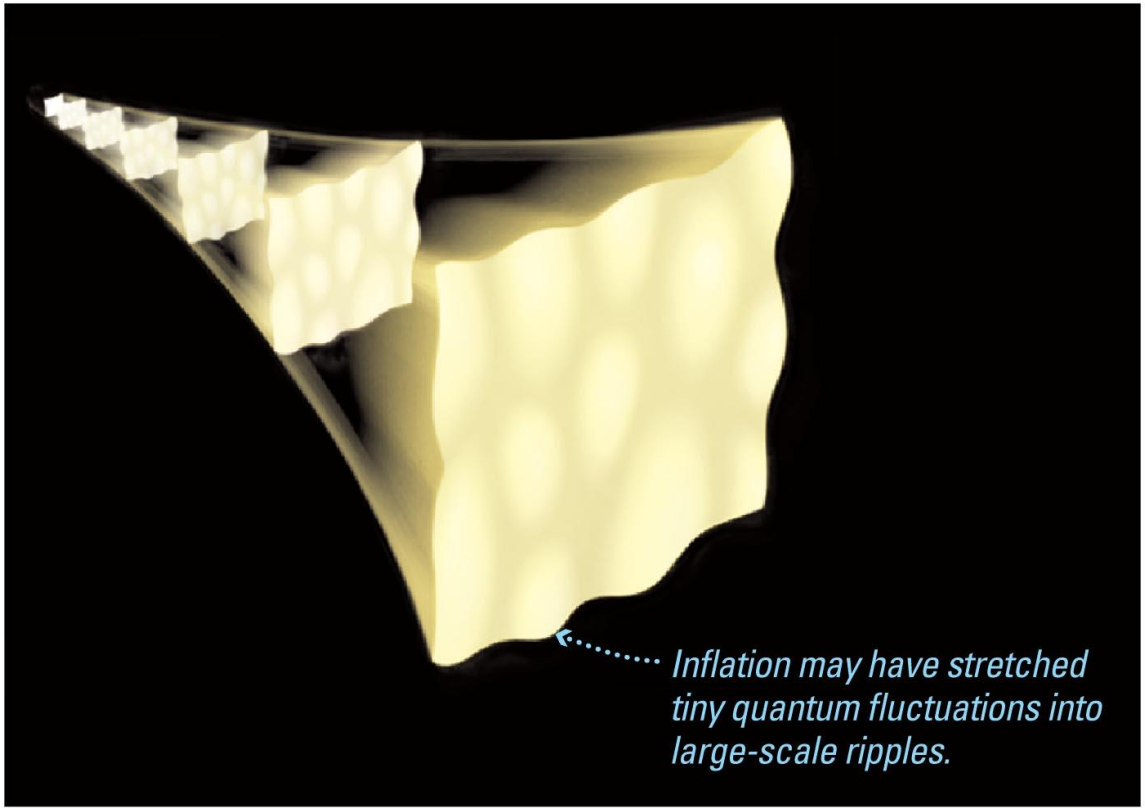
© 2017 Pearson Education, Inc.

Mysteries Needing Explanation

1. Where does structure come from?
2. Why is the overall distribution of matter so uniform?
3. Why is the density of the universe so close to the critical density?

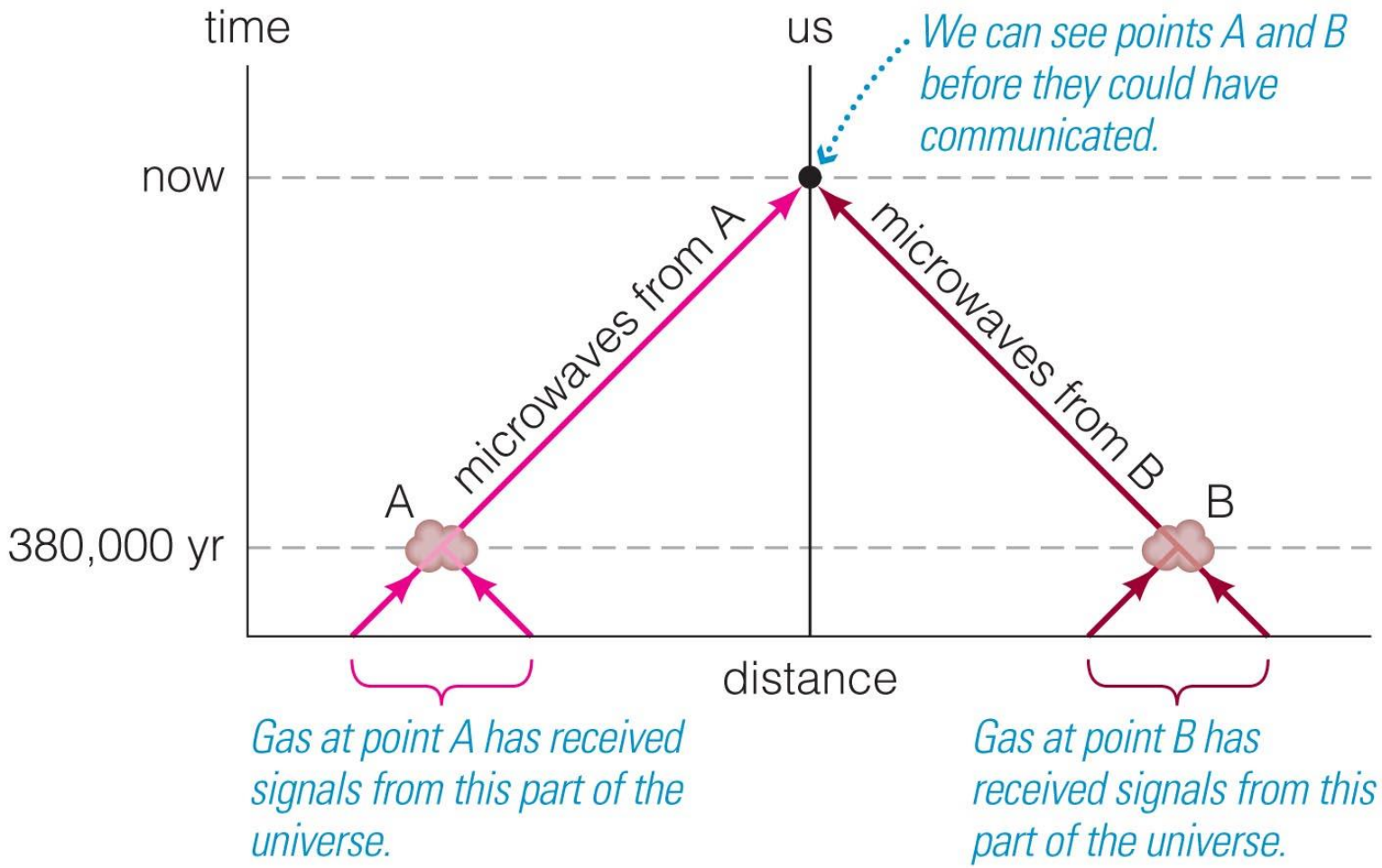
An early episode of rapid inflation can solve all three mysteries!

© 2017 Pearson Education, Inc.



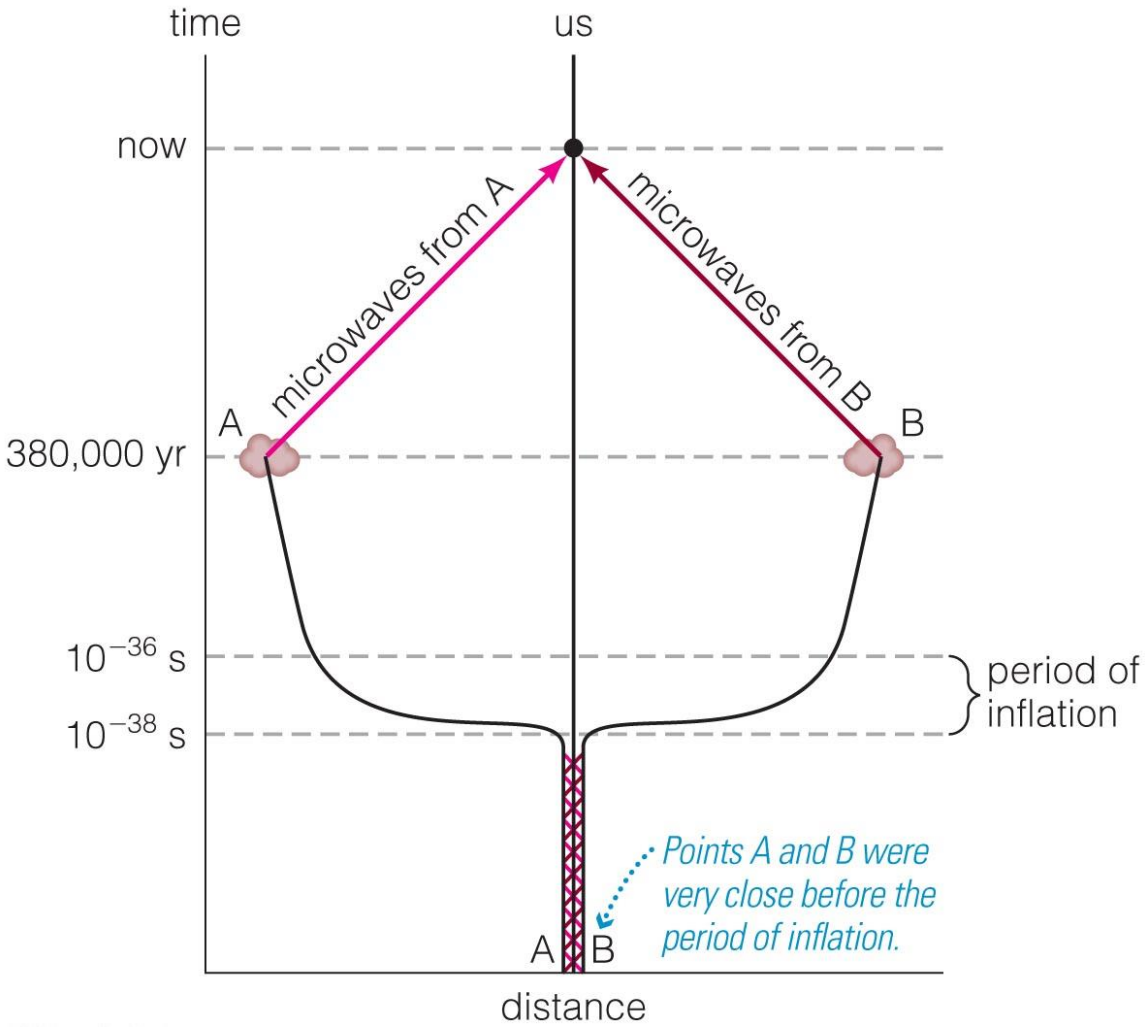
- Inflation can make all the structure by stretching tiny quantum ripples to enormous size.
- These ripples in density then become the seeds for all structures in the universe.

© 2017 Pearson Education, Inc.


time
us
We can see points A and B before they could have communicated.
now
microwaves from A
microwaves from B
A
B
380,000 yr
distance
Gas at point A has received signals from this part of the universe.
Gas at point B has received signals from this part of the universe.

- How can microwave temperature be nearly identical on opposite sides of the sky?

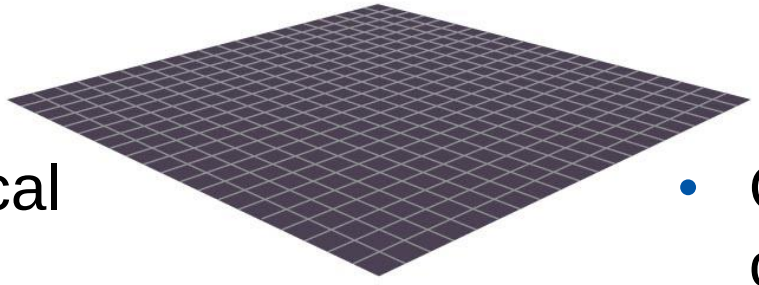
© 2017 Pearson Education, Inc.



- Regions now on opposite sides of the sky were close together before inflation pushed them far apart.

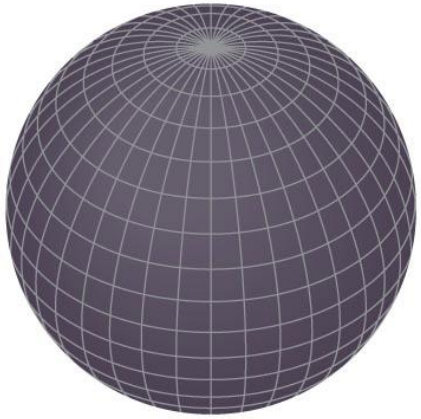
© 2017 Pearson Education, Inc.

- Density = Critical



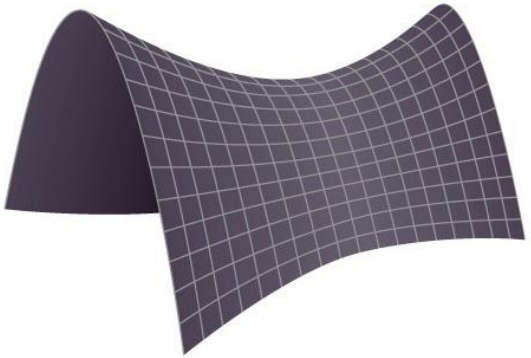
flat (critical) geometry

- Density > Critical



spherical (closed) geometry

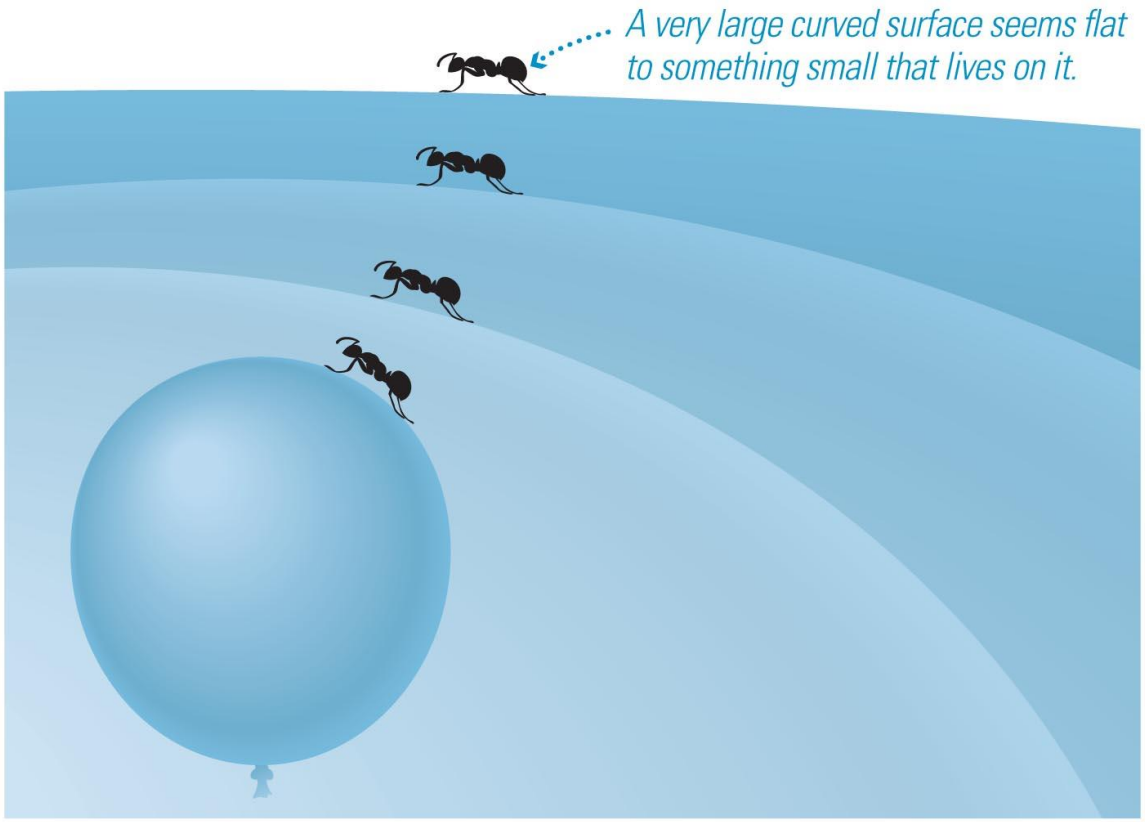
- Density < Critical



saddle-shaped (open) geometry

- Overall geometry of the universe is closely related to total density of matter and energy.

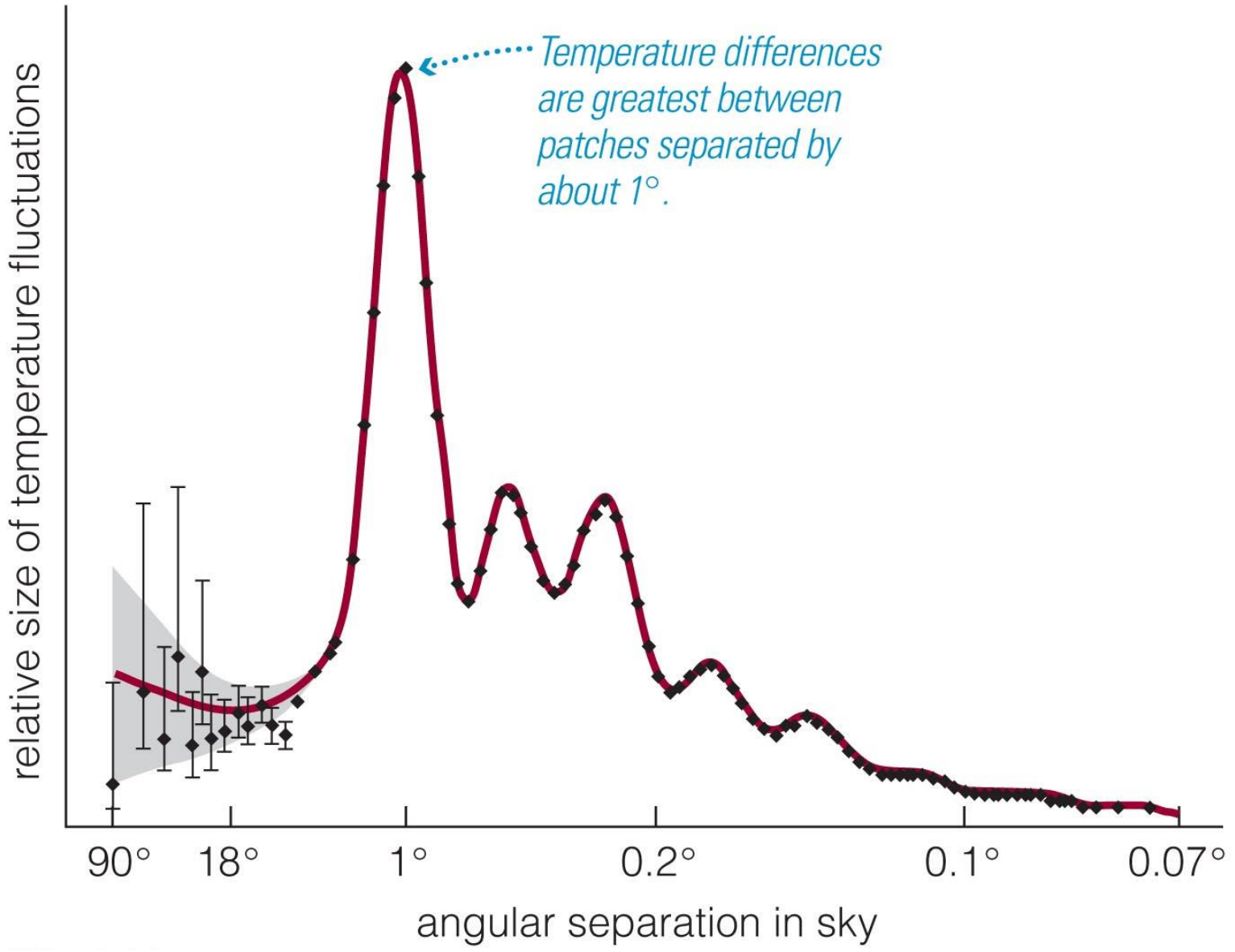
© 2017 Pearson Education, Inc.



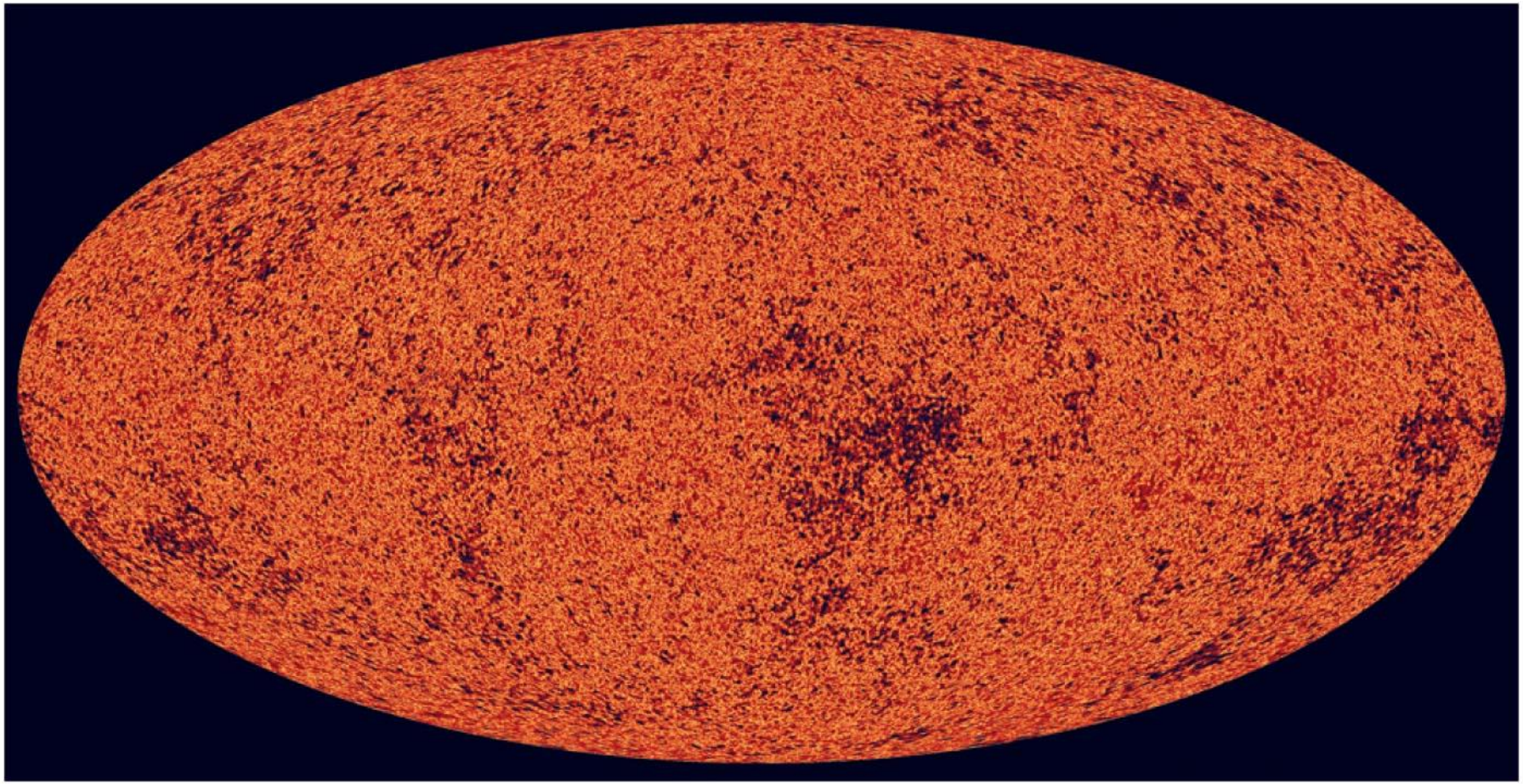
- Inflation of the universe flattens its overall geometry like the inflation of a balloon, causing the overall density of matter plus energy to be very close to the critical density.

© 2017 Pearson Education, Inc.

Did inflation really occur?

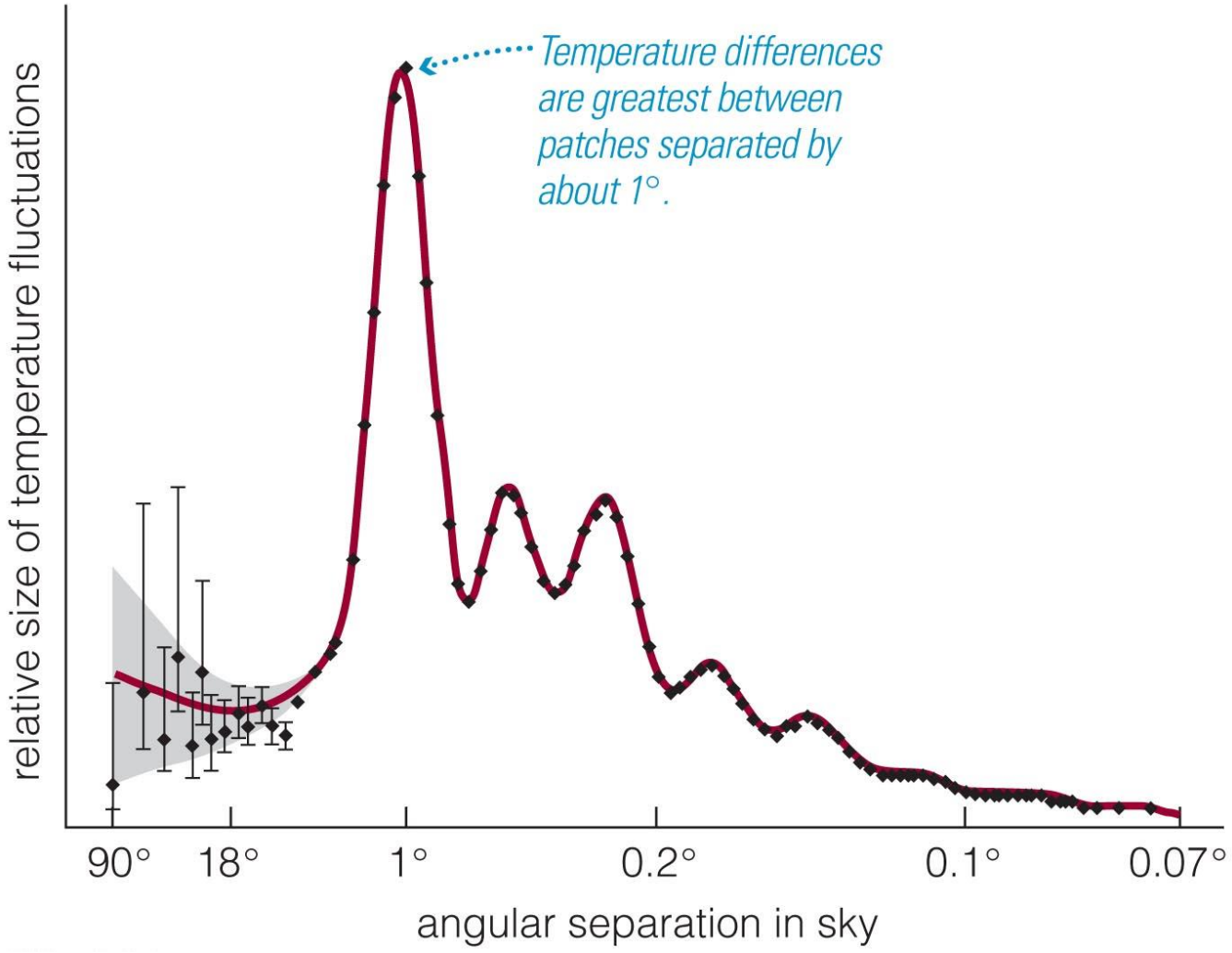


© 2017 Pearson Education, Inc.



- Patterns observed by WMAP show us the "seeds" of structure in the universe.

© 2017 Pearson Education, Inc.



- Observed patterns of structure in universe agree (so far) with the "seeds" that inflation would produce.

© 2017 Pearson Education, Inc.

"Seeds" Inferred from CMB

- Overall geometry is flat.
  - Total mass + energy has critical density.
- Ordinary matter is ~ 5% of total.
- Total matter is ~ 32% of total.
  - Dark matter is ~ 27% of total.
  - Dark energy is ~ 68% of total.
- Age is 13.8 billion years.

© 2017 Pearson Education, Inc.

"Seeds" Inferred from CMB

- Overall geometry is flat.
  - Total mass + energy has critical density.
- Ordinary matter is ~ 5% of total.
- Total matter is ~ 32% of total.
  - Dark matter is ~ 27% of total.
  - Dark energy is ~ 68% of total.
- Age is 13.8 billion years.

In excellent agreement with observations of present-day universe and models involving inflation and WIMPs!

© 2017 Pearson Education, Inc.

What have we learned?

- **What key features of the universe are explained by inflation?**
  - The origin of structure, the smoothness of the universe on large scales, the nearly critical density of the universe.
  - Structure comes from inflated quantum ripples.
  - Observable universe became smooth before inflation, when it was very tiny.
  - Inflation flattened the curvature of space, bringing expansion rate into balance with the overall density of mass-energy.

© 2017 Pearson Education, Inc.

What have we learned?

- **Did inflation really occur?**
  - We can compare the structures we see in detailed observations of the microwave background with predictions for the "seeds" that should have been planted by inflation.
  - So far, our observations of the universe agree well with models in which inflation planted the "seeds."

© 2017 Pearson Education, Inc.

22.4 Observing the Big Bang for Yourself

- Our goals for learning:
  - **Why is the darkness of the night sky evidence for the Big Bang?**

© 2017 Pearson Education, Inc.

Why is the darkness of the night sky evidence for the Big Bang?

a In a large forest, a tree will block your view no matter where you look. Similarly, in an unchanging universe with an infinite number of stars, we would expect to see stars in every direction, making the sky bright even at night.

© 2017 Pearson Education, Inc.

Olbers' Paradox

- If universe were
  1. infinite
  2. unchanging
  3. everywhere the same

  then stars would cover the night sky.

© 2017 Pearson Education, Inc.

- The night sky is dark because the universe changes with time. As we look out in space, we can look back to a time when there were no stars.

a In a large forest, a tree will block your view no matter where you look. Similarly, in an unchanging universe with an infinite number of stars, we would expect to see stars in every direction, making the sky bright even at night.

b In a small forest with a smaller number of trees, you can see open spaces beyond the trees. Because the night sky is dark, the universe must similarly have spaces in which we see nothing beyond the stars, which means either that the number of stars is finite or that the universe changes in a way that prevents us from seeing an infinite number of them.

© 2017 Pearson Education, Inc.

What have we learned?

- **Why is the darkness of the night sky evidence for the Big Bang?**
  - If the universe were eternal, unchanging, and everywhere the same, the entire night sky would be covered with stars.
  - The night sky is dark because we can see back to a time when there were no stars.

© 2017 Pearson Education, Inc.